Electricity Industry Reforms in Thailand: A Historical Review

Supannika Wattana, Deepak Sharma and Ronnakorn Vaiyavuth

Abstract**—** *The Thai Electricity Supply Industry (ESI) has been undergoing reform since the early 1990s. The first stage of reform resulted in the introduction of Independent Power Producers (IPPs) and Small Power Producers (SPPs) programs. This was followed by, in the mid-to-late 1990s, a proposal to introduce a market-oriented reform. This reform program envisaged the separation of generation from transmission and distribution functions; introduction of competition in generation; development of new market-oriented regulatory arrangements, and the privatization of the industry. This reform, argued its proponents, will improve the efficiency of the electricity industry; lower electricity tariffs; improve quality of service; draw private investment into power generation sector; reduce the government's investment burden of financing expensive electricity infrastructure and hence enhance its capacity for investing in other priority programs such as health, education and other social activities. This paper examines the veracity of these arguments. This examination is assisted by a historical review of the evolution of the Thai Electricity Supply Industry (ESI). This review reveals that the above noted arguments are unsupportable on the basis of the technological, economic, environmental, social and political realities prevalent in Thailand. This paper further emphasizes the need to clearly identify the 'real' rationale for reform so that an appropriate reform pathway – consonant with socio-political contexts in Thailand – could be selected.*

Keywords**— Electricity Supply Industry, Historical Review, Reform, Thailand.**

1. INTRODUCTION

Over the last fifteen years, the Thai Electricity Supply Industry has undergone reform in its structure, ownership and regulation. Prompted by concerns about poor industry performance, the Thai government initiated a process of reform of the electricity industry in the year 1992. The first step in the process was the introduction of Independent Power Producer (IPP) and Small Power Producer (SPP) programs with the aim to meet the growing demand for electricity. This was followed by, in the mid-to-late 1990s, a proposal to introduce a market-oriented reform. The main catalyst for this reform was the East Asian financial crisis of 1997/1998. This reform, argued its proponents, will improve the efficiency of the electricity industry; lower electricity tariffs; improve the quality of service; draw private investment into power generation sector; and reduce the government's investment burden of financing expensive electricity infrastructure and hence enhance its capacity for investing in other priority programs such as health, education and other social activities. This paper examines the veracity of these arguments. This examination is assisted by a historical review of the evolution of the Thai Electricity Supply Industry (ESI). It starts with the beginning of electricity, through the industry establishment, to the foundation for privatization, the first step of electricity reform and finally a proposal for a market-oriented reform. This paper also emphasizes the need to clearly identify the 'real' rationale for reform so that an appropriate reform pathway – consonant with socio-political contexts in Thailand – could be selected.

2. HISTORICAL EVOLUTION OF THE THAI ELECTRICITY INDUSTRY

This section provides a detailed description of the historical evolution of the Thai electricity industry. This description is partitioned into five time periods, from the beginning of electrification in the year 1884, to the year 2006. These time periods signify significant changes in the industry's organizations and institutions. For each time period, analysis is carried out to delineate the influence of social, political and other factors on shaping the electricity industry's organizations and institutions, and to explain the reasons behind electricity reforms in Thailand.

2.1 Early Days (1884-1949)

Electricity was introduced in Thailand, in 1884, during the reign of King Chulalongkorn, by Filed Marshal Chao Phraya Surasakdi Montri, after his diplomatic mission to Europe. He first financed, with proceeds from the sale of his inherited land, for 14,400 baht, the purchase of two electric generators and accessories from Britain in order to electrify the army building. When news spread to King Rama V, the general was requested to light up the Royal Grand Palace in Bangkok. The Palace was electrified for the first time on His Majesty's Birthday,

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September 20, 1884. Subsequently, the homes of other Royal Family members were electrified [1]. In 1887, a Danish company gained a concession to run an electric trolley from Bang Kaw Laem to the Royal Palace. The company then expanded into generation of electricity for lighting and set up a permanent generation system using wood fuel [2]. In 1897, this company sold its concession to an American company – Bangkok Electricity Light Syndicate – with a contract that the company had to supply lighting system for all streets and government buildings. However, the firm operated at a loss and later transferred its concession to another Danish company – Siam Electricity Co., Ltd. The office of this company was located at Wat Lieb which later became the head office of the Metropolitan Electricity Authority (MEA).

In 1912, the Electrical Division of the Public Works Department installed another power plant at Sam Sen with 25,500 KW capacity in order to supply power to facilitate the construction of a filtering plant for Sam Sen Water Works and also to distribute surplus power to the public in the northern suburbs of Bangkok. Subsequently, electricity supply in the metropolis was firmly established, with Wat Lieb power plant of Siam Electricity Co., Ltd supplying power for the southern areas of Bangkok and the state run Sam Sen power plant covering the northern areas of the metropolis. When the concession of the private company ended in 1950, the government took over the operation and changed the name to Bangkok Electric Works. In 1958, the government established the Metropolitan Electricity Authority (MEA) by merging Bangkok Electric Works and the Electrical Division of the Public Works Department.

For provincial areas, the government first distributed power supply in Ratchaburi province in 1927 and in Chiang Mai province in 1931. In the early stages, private sector was allowed concessions in power production.

Rural electrification efforts began when government set up a rural electricity division in the Interior Department that built power generating system in the town centre of Nakhon Phanom on the Laos border [3]. The system began generating electricity in 1930. Most of the power plants in those days were small-sized diesel generators and operated only during the night time, thus providing uneven service. Therefore, in order to standardize the power industry in provincial areas, the government established, in 1954, the Provincial Electricity Organization, which, in 1960, became the Provincial Electricity Authority (PEA), to be in charge of power distribution in all parts of the country except in the metropolitan areas.

During this period, there were no common standards for electricity systems – especially the extent to which electricity would be generated in large power plants or by small decentralized systems. The structure of the industry was fragmented. There was decentralized control of the regional/individual power plants. Further, the ownership of the industry was diverse; there were over 200 separate small cooperative, municipal or privately owned utilities [3].

2.2 Industry Establishment (1950-1979)

In this period, international agencies and aid programs began to exert considerable influence on Thai economic policy and development programs. An event with unusual significance for Thai economic history was a World Bank advisory mission in 1957 [4]. The mission aimed to study the economic situation of the country and to provide recommendations for the establishment of national economic planning system. The World Bank argued that the Thai government agencies worked without a guiding vision and thus state initiatives were uncoordinated and ineffective [5]. The Bank, therefore, recommended the setting up of a central planning agency to make a continuing study of the nation's economy, and to draw up plans for its development. On the advice of the World Bank, the National Economic Development Board (NEDB) – a key entity with implication for the economy and polity – was established in 1959. In 1972, its name was changed to the National Economic and Social Development Board (NESDB), in order to emphasize the importance of social development in the development process. NESDB was responsible for preparing five-year development plans for the country. These plans have guided the transformation of Thailand from an agricultural to an industrial economy. The underlying philosophy of economic planning in Thailand is commitment to market economy.

The First Development Plan (1961-1965) was essentially a public expenditure program. The principal objective was to encourage economic growth in the private sector through the provision of basic infrastructure facilities in transport, communications, power, social and public services, and agriculture [4]. This first plan initiated the modern era of development. The government shifted its role from dominating the economy through public investment to becoming a facilitator of private companies by providing fundamental infrastructure. Due to limited domestic savings, foreign borrowings by both the public and the private sectors were brought in to fill the gap. Trade deficits and government budget deficits were common phenomena in Thailand during those years. On the advice of and concessionary financing from USAID and the World Bank, work began on a number of large generation projects [6]. Bhumibol was one of the first of numerous World Bank loans to EGAT for building large-scale dams and power plants. Other dams that followed in the 1970s and 1980s had names little known outside Thailand: Sirindhorn, Sirikit, Sri Nakharin, and Kho Laem [7]. In order to receive concessionary financing from the World Bank, Thailand was encouraged to form state-owned electricity companies [6]. For example, EGAT is largely a World Bank creation; in fact, back in the late 1950s, the Bank insisted that the Thai government create an autonomous, independent power agency, which later became EGAT, as a condition for future power loans. The Bank was not only directly responsible for EGAT's formation, it was EGAT's main source of external financing, and thus exercised an important influence in its attention.

In 1968, the Office of Prime Minister issued the

Electricity Generating Authority of Thailand Act, which established the EGAT by merging several regional state-owned generating authorities. By then, the Thai Minister of Interior enacted the Metropolitan Electricity Authority Act and the Provincial Electricity Authority Act, which in effect established the MEA in 1958 and PEA in 1960. A typical structure of the Thai electricity industry was vertically integrated; for example, EGAT was the sole agency responsible for generation and transmission of electricity to the entire nation. The distribution and retail service functions were the responsibility of MEA (in Bangkok, Nonthaburi and Samutprakarn) and PEA (in the provincial cities and the countryside). By 1981, over 50 % of Thai population had access to electricity [3]. In Thailand, electricity was a practical necessity of industrialization as well as played an important role in national ideology, symbolizing a new type of social compact between the state and citizen. In propaganda and popular consciousness alike, images of a society with universal and affordable electricity became important tropes of state-led development; the conjoining of the electrification enterprise to the majesty of the state can be seen in the expression of Thai peasants – *fay laung,* “the King electricity” [8]. The role of electricity in powering Thailand’s industrialization and the rapid expansion of the organizations involved made the three power utilities very strong politically. By the 1970s, these three power utilities were effectively self-regulating with the exception of basic financial requirements set by the Ministry of Finance [9].

As noted above, the three power utilities were strong politically. It is, however, interesting to note that the most powerful player in the electricity industry is EGAT. This is partly because of its location in the government structure (also see Smith, 2003 cited in [10]). Further, EGAT has not only played a major role in central planning for electricity development but EGAT’s political power has enabled it to influence the privatization policy. For instance, EGAT employees have been rather vocal in their opposition to the privatization of state electric utilities. The recent cancellation of the electricity privatization program was attributed by many to the opposition by EGAT union.

The multiplicity of the institutional regime for electricity as noted above posed some co-ordination problems. For instance, the responsibility for tariffs, capital project proposals, budgets for submissions to the council of Ministers, annual financial performance, and requests for government equity and loans is shared by several agencies including the Committee for Power Policy and Development, the Budget Bureau, the Tariff Rate Committee, NEADB, Ministry of Finance [11]. Often, these are conflicts and none of the agencies has the overall policy responsibility. Decisions are typically made by a consensus of all the agencies, including the three state electric utilities.

2.3 The foundation for privatization (1980-1989)

During this period, several internal and external factors influenced the further development of the industry and laid the foundations for its privatization. Those factors include high public sector debt in the electricity industry due to the oil price shocks of the 1970s; decreasing public and international donor funds for electricity as country planners adopted neo-liberal policies that emphasized reduced public sector; rapid economic expansion which subsequently resulted in rapid electricity system expansion; and institutional revolution.

The Oil Price Shocks of the 1970s

During the period for the Second Plan (1967-1971), there had been a rapid expansion of the electricity system. Much of this expansion was financed by borrowings. Consequently, Thai utilities built up high debt with the energy sector accounting for over 46 % of all foreign loans between 1967 and 1971 [6]. In fact, borrowing had been a key factor in the sector’s strategy to meet the growing energy demands of the Thai economy [11]. But the charged tariff was generally lower than the cost of electricity generation. Furthermore, because of heavy reliance on imported oil, the Thai economy suffered severely from the two oil price shocks of the 1970s. Inevitably, Thai utilities were faced with a substantial debt as a consequence of these two oil shocks. Especially between 1978 and 1981, Thailand’s oil import bill tripled, sparking a debt crisis in which government debt peaked at 39 per cent of GDP [12]. This crisis forced Thailand to undertake a comprehensive economic adjustment program. Thailand took recourse to the IMF and the World Bank to agree on a structural adjustment program and obtain a Structural Adjustment Loan (SAL). Thailand received support from the IMF in the form of Stand-by Agreement in 1981, 1982 and 1985, and from the World Bank through SALs in 1982-83 [13]. The 1981 Stand-by Agreement with the IMF aimed at reducing the public sector deficit and to restore international competitiveness [13]. In 1982-3, Thailand took out structural adjustment loans (SALs) from the World Bank with the conditionality that included increasing energy prices and implementing measures to privatize state-owned enterprises to reduce their colossal debt. However, this first effort to privatize utilities was met with fierce opposition from labour unions of the state electric utilities and independent academics, and finally defeated [6].

Emergence of neo-liberal policies

In the 1980s, there was a world-wide re-emergence of the neo-liberal ideology. Deregulation, privatization and free trade moved into the mainstream of political thought. Criticism of the Keynesian policies and championing of free markets moved rapidly from a few academic citadels and conservative think tank into concrete policy under the Regan and Thatcher administration [8]. The ideology of reducing the role and intervention of government and relying on the market mechanism has subsequently been widely adopted. The economic policies influenced by neo-liberalism were also adopted by the major international organizations such as the World Bank and the IMF [14]. The role of public international financial institutions was transformed as a result of these policies. Traditionally, they had supported the expansion of generation capacity through large-scale projects as discussed earlier. Under the new policies, they shifted their traditional emphasis on economic and social goals from assisting country in its infrastructure development to an emphasis on increasing efficiency, expanding the role of private investment and changing the way government managed electricity industry. As a consequence of this, there was a decrease in support funds – previously provided with low interest rates and long repayment periods – from these financial institutions. These external donors began to make their lending conditional to the government opening up its electricity market to private ownership and competition. As noted above, structural adjustment loans (SALs) was one example of the conditional loans from the external donors. Economy-wide liberalization was coordinated through the vehicle of structural adjustment loans (SALs) [8].

Rapid Economic Expansion

In contrast to the first half of the 1980s, there was a rapid and unexpected economic growth during the period 1987-92. Between 1985 and 1994, Thailand has been one of the fastest growing economies in South-East Asia; its GDP grew at an annual rate of 9.5 percent [15]. This growth primarily resulted from a boom of manufactured exports and the massive inflow of private investment [16]. During the boom period, the annual electricity demand in Thailand increased at the rate of over 10 percent. This rapid growth was brought about by a high rate of urbanization, an aggressive electrification program, a swift expansion in the service and manufacturing industries and a favourable pricing policy which made electricity use more economic than other fuels. This substantially increased demand and caused power shortages. Consequently, the Energy Planning and Policy Office (EPPO) (formerly the National Energy Policy Office of Thailand (NEPO), allowed EGAT to sign several Power Purchase Agreements (PPAs) with independent power producers (IPPs) with contract terms ranging from 1 to 25 years [17]. In order to attract private investment with ensuring healthy profits and low risk to investors, the government provided generous terms for the PPAs. The PPAs were typically structured as 'take-or-pay' contracts which guaranteed IPPs a minimum purchase, whether the electricity was needed or not.

Institutional Revolution

In this period, the government was in transition from military dictatorships towards democracy. Before 1973, the central bureaucracy worked under the control of military rule. A catalytic pro-democracy student uprising in 1973 led to the emergence of a new breed of Thai political figures. Thai politics entered to a new phase. Especially during the Tinsulanonda government (1980-1988), the democratization process in Thailand was gradually enhanced by restoring democratic institutions and maintaining a balance between the political differences of the military, the bureaucrats, and the politicians [18]. Economic interests, and the political parties associated with them, became more powerful as the economy developed. Business interests played an increasingly important role in the House of Representatives. This came in line with the emergence of neo-liberal policies and established the foundations for privatization.

2.4 First step of electricity reform (1990-1997)

Even though the first attempt to privatize the Thai electricity industry was not successful, domestic and international forces remained strong under the government in the 1990s. These led to the formation of the National Energy Policy Office (NEPO) and the rise of IPP program. The creation of NEPO was viewed as the first effort, after the establishment of EGAT, MEA and PEA, to reorganize the institutions involved in the electricity sector. As noted in section 2.2, several government agencies were involved in the electricity policy settings. The rise of NEPO was intended to transfer all the policy responsibility to one entity (i.e. NEPO). NEPO was formed as secretariat to the newly formed National Energy Policy Council (NEPC), which serves as a direct line to the Prime Minister's Office on energy issues. Starting in the early 1990s, NEPO embarked on an ambitious electricity restructuring effort, the first stage of which was the introduction of Independent Power Producers (IPPs), to be followed by full competition in generation, and eventually retail competition [6].

There were also pressures from the external donors. By the early 1990s, international financial institutions sent strong signals that they would no longer be able to provide the financing to expand electricity capacity in developing countries at projected rates [8]. In order to meet electricity demand, developing countries would have to turn to private sector. During this period, these external donor agencies increased pressure to privatize, for instance, by creating barriers to accessing loans for the electricity sector. For example, in 1993, the World Bank put in place a new electricity lending policy. This policy enunciated new conditions for obtaining loans from the World Bank. These conditions included: the establishment of market-based regulatory regimes, commercialization and corporatization of the electricity sector, foreign ownership, and encouragement for private investment [19].

The continuing pressures from the international financial agencies coming in parallel with the rapid rise of electricity demand created a situation which saw private investment as the best alternative. This coincided with the entry of a surplus of private capital searching for investments with high rate of returns and led the initiation of IPP program. The Small Power Producer (SPP) and Independent Power Producer (IPP) programs appeared to be the first steps of electricity reform in Thailand. A brief chronology of ESI reform in Thailand is presented in Table 1. Much of the focus of this reform was to facilitate private participation in electricity generation in order to mitigate immediate electricity shortages. Since 1992, the government has promoted greater role of the private sector in the power generation business, in the form of both SPP and IPP [17]. The purported aim of this initiative was to help reduce EGAT's investment burden and bring down the overall power generation cost to levels that are lower than the generation cost in the public sector.

As a result of IPP and SPP programs, the role of the private sector has been increasing. Figure 1 reveals that the proportion of electricity generated by EGAT decreased from 89 per cent of the gross energy generated in Thailand in 1995, to 49 per cent in 2006. During the same period, the proportion of electricity generated by the private sector increased from 11 per cent in 1996 to 51 per cent in 2006.

The reduction in power generation costs, however, could not be achieved as shown in Figure 2. (Note: These calculations are based on the inclusion of capital expenditure, administrative expense, electricity purchase, fuel expenditure and other energy generation expense).

The reasons for this unsuccessful outcome are the following:

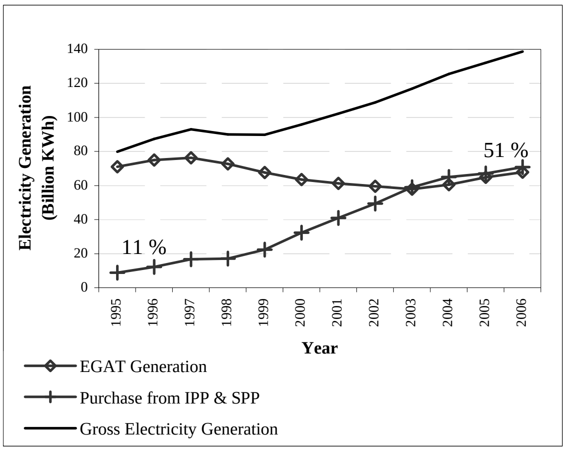
- Although the selection process of IPPs was competitive, the benefits of this, however, did not directly pass to the consumers. IPPs competed only to acquire a license to generate electricity and supply it to EGAT with fixed and long-term PPA.
- Consequently, there was no competition to supply electricity at the cheapest possible price to the final consumers. Usually, the PPAs were signed before the projects start and the projected costs of the IPP projects were overestimated to cover risk. This is a common practice among the IPPs, which informally form a cartel to push up the contract price between themselves and EGAT, finally passing down to the consumers.
- Even if the selected IPPs achieved greater technical efficiencies, the benefits of reduced costs were not passed on to the consumers because of the nature of long term contracts.

The IPP and SPP programs were viewed by many as indicators of success of electricity reform program because these two programs and partial privatization of EGAT's subsidiary received strong interest from both domestic and foreign investors. This encouraged the government to accelerate the market reform program. In 1996, the government passed a resolution that would allow the separation of generation, transmission, distribution business. However, there was strong opposition from the electric utilities to these mores.

2.5 Proposal for market-oriented reform (1998-2006)

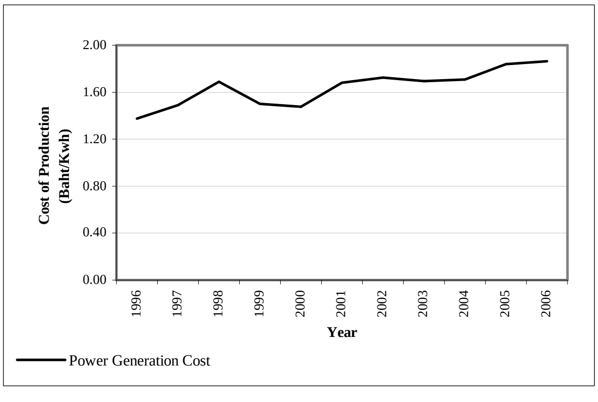
Despite this opposition, the pressures to further reform the electricity industry continued. The Asian financial crisis in 1997/1998 was the main catalyst for accelerating the reform process. This crisis made deep impacts on the whole economy of Thailand including the electricity sector. It resulted in the economic slow down and caused significant decline in electricity demand. This created a condition of excess capacity. The drop in electricity demand combining with the extreme depreciation of its currency made the financial condition of the electric utilities rather precarious. On 14 August 1997, the Minister of Finance and the Governor of the Bank of Thailand co-signed the first Letter of Intent (LOI) committing Thailand to the economic adjustment package outlined by the IMF [14]. According to the first LOI, the government agreed to accelerate privatization in key commercial and infrastructure sectors. The financial woes of the state utilities, coming in parallel with the new IMF loan conditions that emphasized privatization of the utilities, gave a new impetus for accelerating the reform process. As a result of this, the government committed to new structural reforms including privatization of state-owned enterprises in conformance with the agreement for international financial loan and to improve liquidity in the electricity sector.

As previously mentioned in section 2.3, a significant program of private sector participation had already been undertaken in the electricity industry, primarily based on extensive use of the IPPs and facilitation of privately owned distributed generation facilities under the SPP program. The next stage of the industry transformation intended to build on the existing model by creating competitive markets across all elements of the industry. The main emphasis of the second step of electricity reform was to provide a market orientation to the electricity industry by introducing competition in electricity supply and providing choice to customers to select their electricity service providers.



Source: [22]

Fig. 1 Electricity Generation and Purchase in Thailand



Source: [23]

Fig. 2 Electricity Cost of Production (at 2002 constant prices)

Table 1. A brief chronology of ESI reform events in Thailand

Reform Events	Year
Electricity law amendment Establishment of Electricity Generating Public Co Ltd. (EGCO)	1992
Privatized EGCO – subsidiary company of EGAT	1994
IPP law	1996
EGAT privatization plan (Master Plan)	1998
Approval of the principle of establishment of an independent regulator	1999
Establishment of Ratchaburi Electricity Generating Co Ltd. (RATCH) Approval of Price-based power pool model Approval of the draft Energy Industry Act	2000
Proposal for New Electricity Supply Arrangement (NESA) model by EPPO Proposal for Partial liberalization, Cost-based power pool, Transitional model to net pool and Electricity Relation Committee's (ERC) model by EGAT	2002
Abandonment of Price-based power pool Approval of Enhanced single buyer (ESB) model	2003
Postponement of privatization	2004
Establishment of Electricity Regulatory Board	2005
Resignation of regulatory committees in Electricity Regulatory Board	2006
Enactment of the Energy Industry Act B.E. 2550	2007
Establishment of Energy Regulatory Board	2008

Sources: Compiled by this paper from various references

In view of the new institutional arrangements, following the creation of NEPO, the establishment of Ministry of Energy (MOE) in 2002 marked a significant institutional change in the electricity industry. As a consequence of this, NEPO was renamed as the Energy Policy and Planning Office (EPPO) and its policy-influencing role was reduced considerably. Previously, EPPO directly reported to the Minister. Under new arrangements, it reports to the Energy Permanent Secretary [6]. In addition, the state electric utilities: EGAT (formerly under the Office of the Prime Minister), and MEA and PEA (formerly under the Minister of Interior), were transferred to the MOE.

The market-oriented reform prompted the undertaking of several studies about the pros and cons of the reform program. Foreign consultants and local institutions were assigned to undertake studies on the ESI restructuring model and privatization of the state electric utilities. These institutions proposed several reform models which could be summarize as follows.

Price-based power pool

In 2000, the Chuan government approved the introduction of a price-based power pool model. The model was based on the recommendation of a study commissioned by NEPO. According to this study, generation companies would offer competitive bids into a wholesale power pool, while the newly established Independent System Operator (ISO) would be responsible for merit order dispatch, regulated distribution companies would be responsible for power distribution within their areas, and retailing companies would compete in the retailing market. The independent regulator would regulate the natural monopoly (transmission and distribution sections) and also promote real competition in generation and retailing sections. EGAT, MEA and PEA were recommended to split into separate companies and sell their assets to private sectors.

The change of government, from the Chuan to Thaksin government in 2001, however, delayed the implementation of this proposal [14]. This, argue some, was due to the following reasons.

- Concerns from EGAT officials and independent academics were expressed on price volatility, system reliability and adequacy of supply, abuse of market power, environment and impact on unprofitable customers in rural areas.
- The California power crisis and the implementation of the New Electricity Trading Arrangement to replace the power pool in the UK in 2001 stimulated uncertainty about the merits of introducing a power pool in Thailand.
- EGAT employees were strongly opposed to the plan as they argued that the power pool is a risky and expensive electricity trading system. Moreover, they were concerned about loss of job security and benefits, and loss of employment without adequate unemployment benefits.

Another aspect worth mentioning is that the ideology emphasized market forces were reversed during the tenure of Thaksin government. This also played a role in the downfall of the power pool model. With the aspiration of becoming a regional leader and the hub of ASEAN, Thaksin focused on building a strong domestic economy by using partial privatization as tools to achieve national aims, for example, expanding Thailand's economic influence in other countries and boosting the Stock Exchange of Thailand (SET). As a result, the government finally dropped this model and turned to emphasize on partial privatization of SOEs. The Plans for preparing EGAT, MEA, and PEA to be corporatized and listed in the Stock Exchange were approved by the State Enterprise Policy Commission (SEPC) on 20 August 2002 [14].

EGAT VS EPPO

After the power pool model was dropped, the new Thaksin government called for further study on the most appropriate ESI model for Thailand. Several ESI models were proposed by both EPPO and EGAT. In 2002, EPPO proposed New Electricity Supply Arrangement (NESA) which is based on the New Electricity Trading Arrangement (NETA) of the UK. Under the NESA model, the electricity market is fully liberalized in both generating and retailing segments. Bilateral contracts are employed for electricity trading in the liberalized market. During the same time, EGAT proposed the Multiple buyers/Multiple sellers-Partial liberalization (PL) model. In the proposed PL model, the electricity market is partially opened up to allow the large industrial users to purchase power directly from the generators. The proportion of the liberalized market does not exceed 30 per cent of the total electricity demand.

In addition, EGAT appointed two consultant teams to study and recommend a suitable reform structure. A Cost-based power pool was proposed by Kema Consultants and Siam Commercial Bank. Under the cost-based power pool model, all restructuring process is similar to the recommendation of the price-based power pool. The difference is that generators bid at their marginal costs or actual or estimated variable production cost of supply instead of bidding at their willingness to supply. The other model, Transitional model to New Pool, was recommended by the Asian Institution Technology (AIT). In the Transitional model to New Pool model, there are two models recommended for the intermediate and long terms. Under the model for the intermediate term, competition is introduced in generation and separation of generation and transmission is recommended. A System Agent (SAGE) is formed from the remaining units of EGAT after all generating facilities have been separated. SAGE will separate into two bodies, one to operate the power balancing market only and one to operate as a regulated retailer to fulfill the remaining obligation of PPAs. A modified form of IPP arrangement with special PPA is created. In the model for the long term, the proportion of electricity trading through bilateral contracts outside SAGE is expected to grow. SAGE is finally expected to perform a more system balancing role and less electricity trading role under PPA. In the midst of the study period, Electricity Relation Committee (ERC) – a joint management-labour union of EGAT, also proposed the model that claimed to be similar to the model destined to be use in Taiwan. Under the ERC's model, customers are divided into two groups, those in captive market and those in free market. Transmission access is opened to large industry customers. Negotiation would be used to terminate PPAs of IPPs and SPPs. All new private generations compete to sell in the competitive market. In a free market, there is no pool and no buying or selling mechanism created for the free market.

On 23 December 2002, the MOE, through EPPO, organized a seminar on ESI reform to brainstorm and discuss about the optimal ESI model by comparing the current structure with the models discussed above, particularly in relation to electricity system security, competition, tariff, regulation, quality of service and public share offering. The deliberations at the seminar were, however, unable to develop a consensus on a specific model. Finally, the models proposed by both EPPO and EGAT were dropped by the Thaksin administration because there was no consensus about the ESI model and privatization among EPPO, EGAT, MEA, PEA, the private sectors and academics, resulting mainly from the different incentives of each agent. For example, EGAT, MEA and PEA prefer to stay in a monopolistic manner and support the ESI models that do not allow them to separate. The government would like to unbundled the industry and then privatize the SOEs as fast as possible to promote capital market development without serious consideration on the ESI model.

Enhanced Single Buyer (ESB)

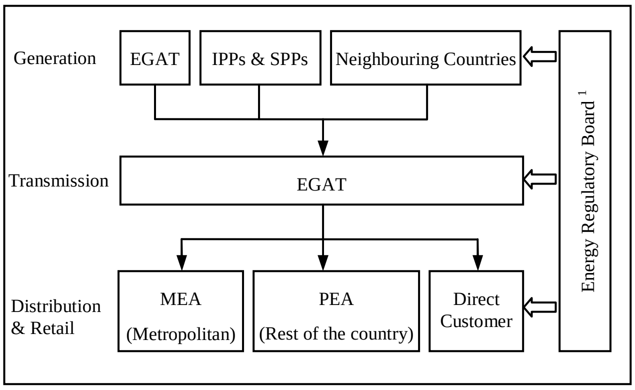
On 9 September 2003, the Cabinet approved the cancellation of the Cabinet resolution of 25 July 2000 on the ESI reform and the establishment of power pool and assigned the MOE to conduct further study on the ESI model. At this time, it seemed that the future direction for the ESI restructuring model was unclear, however, the Cabinet approved to corporatize the whole EGAT as a public company under Corporatization Law.

After being tasked by the Cabinet on 9 September 2003, MOE hired Boston Consulting Group (BSG) to conduct a study on strategies for the development of Thailand's energy sector and the power sector efficiency improvement program. This study includes studies on ESI model, the regulatory framework and the tariff mechanism for Thailand. The BSG proposed five alternative ESI structures: Full Competition (FC) model, Competitive Bilateral Contract (CBC) model, Partial Competition (PC) model, Enhanced Single Buyer (ESB) model and Super National Champion (SNC) model. In September 2003, a steering committee was formed to advance strategies for the development of Thailand's energy sector and power sector efficiency improvement program. The committee discussed the reform model proposed by the Boston Consulting Group and agreed that the ESB model was the best alternative that should be adopted not only for ESI restructuring in the foreseeable future, but also to facilitate the process of corporatization and privatization. The ESB model is quite similar to the current ESI model (single buyer model). The ESB model is different from the current model in that there will be an account unbundling of EGAT's generation and transmission businesses, and any new IPPs will have to compete directly against EGAT's generation. Further, thirty per cent of EGAT would be sold on the stock exchange to raise capital so that the monopoly could stand a better chance against the international competitors at the regional level.

The success, as claimed by the government, of the Petroleum Authority of Thailand (PTT) privatization, in 2001, gave the impetus for accelerating the privatization of state electric utilities without restructuring. Due to the reversal of the economic policy by the Thaksin government, the idea of creating competitive market for electricity was replaced by building EGAT as a *National Champion* by adopting the ESB model. This made the disappearance of choice and competition but instead continued to focus only on privatization of the industry. The initial public offering (IPO) of EGAT, MEA and PEA were scheduled in the first, third, and fourth quarters of 2004, respectively. However, following renewed protests from EGAT and other labour unions, the Thaksin government decided, on 23 February 2004, to put the privatization of EGAT on hold indefinitely.

In early 2005, the Thaksin government was re-elected and the privatization program of state enterprises was revived. EGAT was the first public enterprise to be corporatized in April 2005, and it was scheduled to be listed on the Stock Exchange in October 2005. A group of NGOs and labour unions filed a petition with the Supreme Court a few days before the scheduled listing. On 23 March 2006, the Supreme Court ended the privatization of EGAT by revoking two Royal Decrees that led to its corporatization in 2005. As a consequence of this verdict, EGAT will remain a state enterprise and the plans for its stock market listing were cancelled [24].

With the view to provide effective regulation, the Thaksin government established the interim regulator, namely the Electricity Regulatory Board, on December 1, 2005 [25]. This regulatory board was temporarily established because it was expected that the permanent regulatory authority would be established by the Energy Industry Act.



Note: [1] The Energy Regulatory Board was established in February, 2008

Fig. 3 Current structure of the Thai electricity industry

The September 2006 military coup put on hold further changes to the structure of the electricity industry. It also resulted in the resignation of the interim regulators. In December 2007, the government enacted the Energy Industry Act B.E. 2550 which emphasized the establishment of the Energy Regulatory Board and the Energy Regulatory Office. The Energy Regulatory Board was established on 1 February 2008. This regulatory board is responsible for regulation of the energy sector including electricity and gas. This independent regulatory body is expected to help increase transparency, creditability and public participation in the energy sector decision-making. Figure 3 illustrates the current structure of the Thai electricity industry.

3. RATIONALE FOR ELECTRICITY REFORM IN THAILAND

3.1 Purported rationale for a market-oriented reform

As mentioned earlier, a market-oriented reform was proposed for the Thai ESI in 1998 in the form of the Master Plan. The Master Plan provided guidelines, principles, and practices for increasing effective private sector participation in the economy and served as the basic blueprint for this reform. The main underlying principle of this plan was to deregulate the industry wherever possible to increase competition. This reform (emphasis only on privatization plan), argued its proponents, will [26], [27]

- reduce the investment burden of he government as well as the public sector debt;
- improve the economic efficiency of the industry, as measured by decreased costs of production and/or price of service;
- improve quality of service, including enhancing consumer choice;
- complete needed infrastructure investment projects;
- reduce subsidies and loan guarantees to state electric utilities;
- utilize the proceeds from the sale of state electric utilities for reinvestment in the economy and social sector;
- improve and/or expand services;
- create new employment opportunities; and
- enhance government ability to invest in social and public services.

A deeper review, however, reveals that the above noted arguments are unsupportable on the basis of the technological, economic, environmental, social and political realities prevalent in Thailand. The following discussion provides support to this claim.

Attract private investment

Attracting private investment is one of the major arguments for reform. Such investment clearly depends on investor confidence in the country’s economy which is typically shaped by the political and institutional climate for economic policy, legal system and control of corruption. In Thailand, the constitutions and governance philosophies are combination of the traditional and modern western style [28]. Thai politics have traditionally involved a delicate balancing act between the crown, the army, the bureaucracy and powerful economic interests [29]. Political and legal frameworks are weak. Corruption is widely perceived to be a serious governance problem. Transparency International's 2007 survey listed Thailand as 84th out of the 179 countries surveyed with Corruption Perception Index (CPI) equal to 3.3 (on a zero to 10 scales, with 10 being least corrupt) [30]. The Opacity Factor for Thailand for 2004 was 35 (0 indicates best and 100 indicates worst) [31]. This factor represents the five key dimensions that affect capital market, namely corruption, legal system, economic policies, accounting standards and practices (including corporate governance and information release), regulatory regime [31]. Such climate, therefore, would not inspire much investor confidence. Moreover, the political and policy uncertainties associated with the military coup also have contributed to lowering investor confidence.

Reduction in electricity prices

The argument that electricity reform would lead to a reduction in electricity prices does not appear to be supportable on the basis of available evidence. According to Sharma [32], 'Electricity generation accounts for nearly two-thirds of the total cost of electricity supply... In a situation of excess capacity, competition in generation has a potential to exert downward pressure on the cost of electricity production'. But electricity system in Thailand still confront with a condition of capacity constrained system. Therefore, it is unclear how the competitive pool would lead to a reduction in electricity prices. In contrast, it seems that the cost of electricity production is likely to be higher as a consequence of environmental concern. In recognition of global warming, there is now pressure for generating electricity from environmentally benign fuels.

Besides, Fathollazadah and Sharma [31] stated that 'it is widely known that electricity in the ASEAN region is sold at subsidized rates and it is also common knowledge that electricity is priced below it marginal cost in most countries in the region'. In fact, the proponents of reform argued that subsidies should be removed in order to reflect marginal cost of production. Consequently, removal of subsidies clearly could not lower electricity price.

On the question of removal of subsidies, it needs to be viewed in a larger socio-political context. Subsidies provide considerable benefits to consumers who have generally low levels of income and electricity requirements. As a consequence, removal subsidized electricity to this group of consumers may not only socially undesirable but politically unfeasible as well [31].

Enhancing consumer choice

Providing choices to consumer to select their service providers seems to be meaningless when viewed in the context of Thailand where: 10 % of the population remain under the national poverty line of 1386 Baht per person per month, only 1 % in urban but 13 % in rural areas; 84 % of the population live in rural areas and generate income from agriculture-related activities; the distribution of income in the country is highly skewed, with the top 20 percent earning nearly 12 times more income than the bottom 20 percent in the year 2007; the GINI coefficient (commonly used indicator of economic inequality) for Thailand for 2004 was 0.49 (0 indicates perfect equality and 1 indicates perfect inequality) [33]. It is evident from the above discussion that a majority of the poor live in rural areas where it is uneconomic to extend electricity supply. These people do not have the capacity to exercise choices or even to pay their electricity. Consumer choices, therefore, appear to be insignificant for them.

New employment opportunities

The electricity market reform, argued its proponents, would lead to create new employment opportunities. This argument appears to be unjustified. It was, in fact, argued by multilateral agencies, international banks and financial institutions that the Thai electricity industry was inefficient. Such inefficiency, it was further argued, resulted from overstaffing, poor management, inefficient operation and uneconomic pricing practices. The expectation that electricity reform would lead to create new employment, therefore, contradicts itself with the causes of electricity reform

In fact, even in developed countries, for example Australia, which implemented electricity market reform since 1991, a number of people employed in its electricity industry have continued to decline since the onset of reform [34].

Other benefits of electricity reform

Benefits of reform in terms of improved service, enhancing government capacity for investing in other social and public services do not appear to have any reference point for convincing the possibility of the argument. A belief in the success of electricity reform in other countries (mainly developed countries) and in replicability of such success for Thailand appears to be baseless. The economic, political, social and cultural backgrounds of those countries are significantly different from Thailand. These backgrounds are important for designing reform program because they reflect several dimensions of reform and critically influence the feasibility of reform program and hence the outcomes that could be achieved from them.

The earlier discussion suggests that much of the underlying arguments for reform are untenable. There are inconsistencies between the purported rationale and realities prevalent in Thailand. The discussion further reveals that the planners aim to achieve a rather diverse and wide range of objectives from reform, for example, attracting private investment, improving quality of service, developing capital markets, and ensuring economic prosperity. There does not appear to be any compelling logic behind these objectives. For instance, how the electricity price (currently below marginal cost) could be decreased. The outcomes of this reform, therefore, are unlikely to be desirable.

3.2 *'Real' rationale for electricity reform*

A historical review of the Thai electricity industry (Section 2) has revealed that the 'real' rational for electricity reform was different from what are argued by the proponents of electricity reform (As presented in Section 3.1). The ‘real’ rationale, it is argued, has its roots in several internal and external developments and influences. For example:

- One major influence behind electricity reform was pressures from the international financial institutions such as the World Bank, IMF and Asian Development Bank. These institutions, especially the World Bank, played a significant role in promoting, strategizing and even compelling electricity reform in Thailand. For example, the structural adjustment loans (SALs) which Thailand took from the World Bank, in 1982-3, came with conditionality that included implementing measures to privatized state-owned enterprises. In fact, it should be evident from the earlier discussion that the World Bank and other international agencies have continuously played an important role in shaping the Thai electricity industry since 1960s.
- Another significant influence for electricity reform arose in the context of major economic crisis, for example, the oil price increases of the 1970s and the Asian Financial Crisis in 1997/8. As discussed above, these crises created opportunities for the international donor agencies to impose new funding conditions on developing countries; resulted in economic-wide reforms – conditions outlined by the donor agencies. For example, market reforms under the Structural Adjustment Loans (SALs) and the Letter of Intent (LOI) by the World Bank and IMF respectively. More interestingly, the undertaking of electricity reform was included in both of these two programs.
- Domestic forces were also important. The process of democratization led to the emergence of new liberal business leaders. Therefore, the political ideology changed in favour of the market. Previously, the government considered electricity as a vital ingredient for social and economic development of the citizens. Accordingly, the government took all responsibility for electricity provision. It resulted in the establishment of vertically-integrated public monopoly structures. Under the market-oriented political leadership, the government created space for the private sector in electricity development. The economic crisis also created a political opportunity for the market-oriented government to implement privatization policy. Privatization appeared to the government as a vehicle of attracting private capital flows to address fiscal crises.
- Allegation by some that self-interest by the ruling elites was also a significant factor behind electricity privatization. Some of the business-oriented politicians with dual roles – as citizens’ representatives and as executive directors of companies – played a part in promoting the privatization of the industry. They stood to gain personally from the transfer of public resources to the private sector. The example of this was given by Palettu [35] in the case of PTT experience.

This review also suggests that the sequence of steps undertaken to reform the electricity industry in Thailand was somewhat out of synchronism. For example, the establishment of the strong, credible, and independent regulatory body should have preceded industry restructure. It seems, however, that the whole program was focused on the industry privatization. Consequently, it appears only the economic dimension of the program received attention and other dimensions were ignored. Since electricity reforms have widespread ramifications which extend into economic, social, environmental, and political spheres of society, the government should put more focus on these ramifications. Reform design, the authors argue, should be based on broader objectives including sector-finance viability, adequate investment in new generation, reliability of supply, equitable access of supply, promotion of social equity, environmental protection and effective regulation. Also, regulatory reform is a prerequisite for the effective implementation of the reform program and for the ongoing governance of the industry. A regulatory process with high degree of transparency, accountability, and provision for public participation would contribute to good governance of the electricity sector. This would help achieve balance between various interest groups, for instance, public, consumers and investors.

4. CONCLUSIONS

This paper describes the historical evolution of the Thai electricity industry with emphasis on the internal and external forces that have shaped such evolution. It then examines the veracity of purported rationale for electricity reform in Thailand. A review of the Thai electricity reform reveals that the purported rationale for a market-oriented reform is unsupportable on the basis of the technological, economic, environmental, social and political realities prevalent in Thailand. This is because the socio-economic realities in Thailand are not conducive to the undertaking of market reform as proposed. These realities include macroeconomic conditions, its power system, its political situation, the size of country and the capacity of its domestic financial market and institutions. This paper also recommends that regulatory reform should be undertaken prior to structural reform.

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Energy Challenges for Thailand: An Overview

Srichattra Chaivongvilan, Deepak Sharma and Suwin Sandu

Abstract— *Thailand is one of the most dynamic countries in South-east Asia. Energy has traditionally played a vital role in its economic growth. Currently, over 50% of the energy consumption in Thailand is imported. The energy demands are expected to increase by approximately 4.5% per year over the next decade. The future economic prosperity is, therefore, dependent on the provision of adequate energy. In order to ensure such provision, effective national energy policies would be needed. This is likely to be a challenging task. This paper examines if the current energy policies are adequate to meet this challenge. The examination reveals that the current policies are not adequate. This paper further recommends the need to develop a comprehensive framework that could be used to analyse the economy-wide impacts which could provide guidance for the development of appropriate energy policies.*

Keywords— **Energy Challenge, Institution, Policy, Thailand.**

1. INTRODUCTION

Energy is essential for social and economic well-being of a nation. More so, energy in developing countries is needed to raise the level of vast majority of population from subsistence to self-sustaining levels. Consequently, the demand for energy has increased rapidly in the developing countries. According to [1], ‘The process of economic development in the developing countries has involved a strong growth of energy demand over the last 50 years’. Thailand is one of the most dynamic energy-intensive economies in South-east Asia [2]. Over the last three decades, its total primary energy consumption has increased rapidly, from 8,642 thousand tonnes of oil equivalent (ktoe) in 1973, to 85,189 ktoe in 2005 – an average annual growth rate of 7.2%. In comparison, the average annual growth rate of GDP over this period was 4.2%. This increasing energy demand was mainly due to industrialisation, urbanisation, and economic growth [3]. It is also worth noting that the economic and energy growth took place in an environment of static, indeed declining population growth. For example, the population growth rate in Thailand decreased from 0.93% in the year 2000 to 0.66% in the year 2007 [4]. It is expected that the future energy demand would increase mainly due to the expansion of intensive energy manufacturing, road transport, and rural and urban development. According to [5], if Thailand’s current energy trends do not change (that is, in the business-as-usual scenario) in the years to come, the primary energy demand in the year 2025 would be 186,659 ktoe, as compared to 85,189 ktoe in 2005. Clearly, the provision of adequate energy supply is essential for Thailand in order to promote economic growth. To ensure such provision requires effective energy policies. The design of effective national energy policies is however likely to be a challenging task for Thailand due to a variety of internal and external factors. This paper identifies major energy challenges faced by Thailand and examines if the current policies are adequate to meet these challenges.

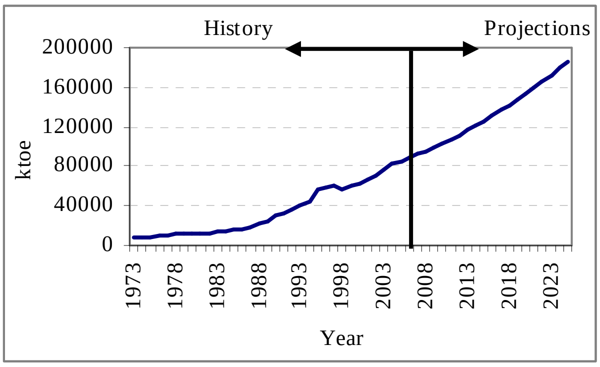

Fig.1. Primary energy demand and projections [4], [6]

2. ENERGY CHALLENGES

In view of the significant energy requirements to develop the country, along with the dependency of economy on foreign fuel, and global development, Thailand undoubtedly faces several challenges to ensure the provision of reliable and affordable energy supplies. The main issues that underpin these challenges include the following.

2.1 Energy-economic interactions

The Thai economy has grown rapidly and so has energy consumption over the last 30 years. Figure 2 shows Thailand’s average annual growth rate of GDP and energy consumption over the period 1972-2006. The figure suggests that there is a correspondence between energy consumption and economic growth. Prior to the 1973 energy crisis, Thailand’s rate of energy consumption, which grew by 15% in the year 1973,

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reduced to minus 4% in the year 1974. Again, Thailand's energy consumption and hence economy were impacted by the second oil shock of 1979. The average annual growth rate of GDP of 10.7% in 1978, declined to 1.8% in 1980. And, the growth rate of energy consumption fell from 3.2% in 1978, to minus 1% in 1980. The figure also shows that Thailand's energy consumption was strongly affected by the 1997 East Asian financial crisis. The Thai economy which expanded by 2.2% in the year 1996 shrank by 36% in the year 1998. And, energy consumption growth rates for the years 1996 and 1998 were 10.8% and minus 7%, respectively. These statistics reinforce the strength of the relationship between energy and economy, and also shows the influence of the world's energy and economic events on Thailand.

Due to the limited indigenous energy resources, Thailand is strongly dependent on imported fuels, which are important for country's economic development. Many of those fuels are obtained from politically volatile regions, for example, the middle-east. Any geo-strategic volatility in these regions is likely to have perceptible impacts on the world economy and, by implication, Thailand. The ongoing high oil price and its anticipated influence on the balance of payment account for the country and consequential slow-down of economic growths is just a case in point.

2.2 *Security of energy supply*

There has certainly been increasing recognition of the importance of energy security since the 1973 energy crisis. A significant portion of the oil and gas demands are imported to maintain the country's economic development. Since the 1990s, Thailand's total primary energy mix has been heavily dominated by oil (about 50%) [7]. In the year 2005, Thailand's oil consumption was 910 thousand barrels per day, whereas oil production was only 330 thousand barrels per day, which meant that Thailand imported nearly 570 thousand barrels of oil per day [8]. Even though Thailand has large proven natural gas reserves and natural gas production increased significantly over the last few years, the country still remains reliant on imports of oil to meet growing domestic fuel demand. In 2005, for example, over 95% of crude oil requirements were imported and it cost the economy around US$13 billion – approximately 9.6% of 2005 GDP [2]. According to [9], 'Thailand is facing major challenges concerning its energy supply, as natural energy resources are fast depleting, leading to an insufficient supply of energy to the private manufacturing and service sectors, as well as the general public'. Thus, ensuring the security of energy supply is the major challenge for Thailand.

2.3 *Energy investment requirements*

Thailand energy consumption is forecasted to grow at an average rate 4.5% to sustain economic growth of 4% per annum to the year 2025 [4]. This increased energy demand would require significant investments in the energy infrastructure, for example, according to [10] Thailand would require a total investment of $168-211 billion to the year 2030 for the expansion of electricity generation capacity, transmission, including oil and natural gas infrastructure. To meet the rising demand for energy, Thailand has made rigorous efforts to expand domestic production. It has also tried to promote private participation in the energy industry. However, these efforts were stalled in the year 2006, due to political and societal constraints. The challenge to attract new investments therefore stays.

2.4 *Environmental impacts*

Figure 3 shows the relationship between carbon emissions and economic growth. As Thailand's economy recovered from the 1997 financial crisis, the government has pursued policies that promoted new investments to rebuild country's industrial base while increasing other measures, such as international cooperation and environmental protection. Thailand signed the Kyoto Protocol on 2 February 1999, and ratified it in August 2002. However, carbon emissions increased by almost 4,000 thousand metric tons of carbon between 2001 and 2002, despite Thailand's ongoing efforts to improve environmental quality [11]. Thailand is now faced with the consequences of environmental degradations resulting from carbon combustion. The future soaring energy demand is likely to worsen the country's environmental situation. And any environmental policy aimed at, say, reducing carbon-dioxide emissions from the energy sector, is likely to constrain economic growth. The pressure to reduce carbon-dioxide emissions is however real and therefore the question of reconciliation between environment and economy has emerged as a significant policy challenge. This challenge is compounded by the fact that Thailand currently does not have any coherent policy framework to address environmental issues.

2.5 *Social impacts*

Energy is a key factor in our daily life. Directly and indirectly, energy policies affect society. According to [12], 'Because of the direct relationship between productivity and energy use, a main premise is that social and economic structures could be substantially and regressively altered by large energy use constraints'. Further, according to [13], 'To make efficient policies, the analysis of the distribution impact of policy on social acceptances is the requirement'. The social impacts of energy policies include employment, equity of prices and consumer interests [14]. Several works, for example [15] and [16], have expressed concerns about the lack of consideration of social impacts in the current Thai energy policies, especially related to electricity reform policies. According to [17], 'A recurring theme in Thai history is that the power sector does not receive a level of attention from civil society in proportion to its significance to Thailand's economy, environment and society…very few players submitting ideas for public discussion and even fewer analytically rigorous discussions of options, approached and strategies'. The overlooking of the social impacts could render the policies meaningless, and result in a waste of time and money. The cancellation of the Thai Electric Supply Industry (ESI) privatisation plan in the year 2006 is a case in point.

2.6 Political influences

Thailand's policy institutions are numerous, spread over different ministries sections and departments, often operating in an isolated manner. Under the Administrative Organisation of State Affairs Act (No.5) BE. 2545 (2002), these units are purportedly meant to function in a unified manner. The Office of the Prime Minister is the central body, which in itself ranks as a ministry. The responsibility of this office is largely concerned with formulating and detecting the conflicts in the national policy [18]. As the Office of the Prime Minister is under the direct command of the Prime Minister and the cabinet, the approvals of policies are influenced by the political preferences of the Prime Minister. Political constraints therefore could interfere with the need for effective policy development, especially if the political system is corrupt. Figure 5 and 6 show the structure of energy institutions before and after the 2002 institutional arrangements.

2.7 International conflicts

Thailand is an important member of several international organisations, such as WTO, APEC, ASEAN and GMS. A number of agreements have been signed in order to strengthen the relationship and political power in the region. Occasionally, some of agreements have conflicted with national policy agendas. For instance, Thailand wishes to import more energy from neighbouring countries; however, national policy emphasises decreased import dependency. Such conflicts could obviously affect other sectors of the economy.

The issues noted above suggest that the development of an appropriate energy policy is likely to be a challenging task. The following sections of this paper analyse if the current energy policy environment in Thailand is adequate to meet this challenge.

3. A REVIEW OF ENERGY INSTITUTIONS

The energy system in Thailand can be categorised into two major industries, namely, petroleum and electricity. Both these industries are currently under the command of the Ministry of Energy – the apex energy planning and policy institution in Thailand. This paper focuses on the evolution of national institutions for energy planning and policy.

The evolution of the energy policy institutions in Thailand, examined in this paper, can be classified into 5 periods: absolute monarchy (before 1932); World War II and international influences (1932-1970); the expansion of state-owned utilities (1971-1980); financial liberalisation (1981-1997); and the reform era (1998-present).

Absolute monarchy (before 1932)

Before 1932, Thailand purchased oil and petroleum from two foreign companies, namely, Standard Welcome Oil Company and Royal Dutch Petroleum Company. As there was no competition, the prices of energy depended solely on the prices set by these companies. As a result, Thailand was forced to pay higher prices for energy, compared to the world energy prices. Oil and petroleum were strictly consumed in the households, transportation and military sectors. Electricity was available only to the wealthy families.

World War II and international influences (1932-1970)

Thailand became a constitution monarchy in the year 1932. The Energy Division was established in 1933, worked under command of the Ministry of Defence. This initial energy policy institution was responsible for national energy planning and policy development, and energy trading. In the year 1937, the Energy Division was upgraded to be the Department of Energy.

World War II began in the year 1939 and caused economic and identity crises for the country. Thai people suffered from essential commodity shortages, increased taxation and high inflation [17]. The main electricity station was destroyed during the war. However, the establishment of the oil refinery at Chong Non-See in the year 1940 assisted Thailand to deal with this critical situation.

In the year 1945 after World War II, Thailand was forced by foreign companies and the United Nation's agencies to open its petroleum market. Under this pressure, the government, under Prime Minister Kuang Apaiyawong, decided to let foreign companies take control of the country's oil refinery and all of petroleum businesses in 1946. The Department of Energy was disbanded. However, the Energy Division and Energy Stock Organisation still remained, primarily for military reasons. In 1953, the Energy Division was upgraded to be the Department of Energy and Defence. The government decided to assume control of the country's energy business again. The Chong Non-See oil refinery station was taken back from foreign companies, and it started producing petroleum under the authority of the Thai government in 1957. In this period, the demand for electricity increased rapidly. As part of this development process, the National Energy Authority (NEA) was created in 1953, under the National Energy Authority Act, reporting directly to the Ministry of Prime Minister. [17], cited in United Nations (1963), explained the responsibilities of the NEA: 'NEA was responsible for the planning and coordination of schemes for development and utilisation of all energy resources in the country'. In the year 1959, Bangchak oil refinery station was established with the capacity to produce 5,000 barrels per day of petroleum. The Metropolitan Electricity Authority (MEA), the Provincial Electricity Authority (PEA) and the Electricity Generating Authority of Thailand (EGAT) were created in the years 1958, 1960 and 1968, respectively, responsible to act as state-owned enterprises in the electricity sector.

The expansion of state-owned utilities (1971-1980)

The rise in world energy prices in the year 1973 strongly impacted the Thailand economy; Thailand's oil import dependency was 95% at that time [4]. The governments began to consider alternative energy sources instead of imported fuel. The Natural Gas Division was established in 1977, responsible for exploring domestic natural gas resources. The Petroleum Authority of Thailand (PTT) was established in 1978, to work as a state-owned enterprise in the petroleum sector. During this period, the state-owned enterprises rose in power, and the role of NEA declined.

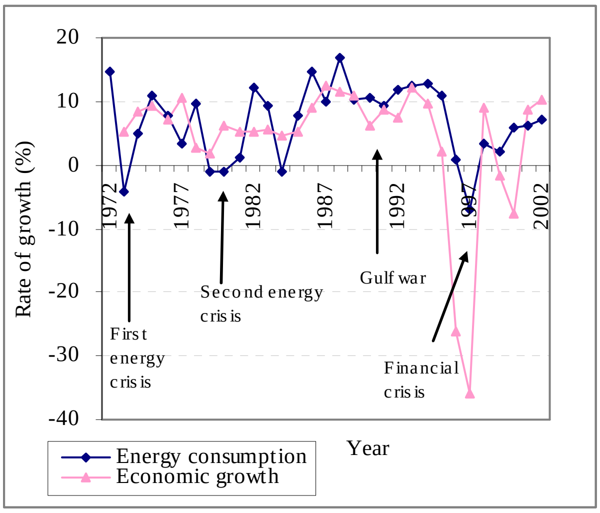

Fig.2. Energy consumption and economic rates of growth [6], [19]

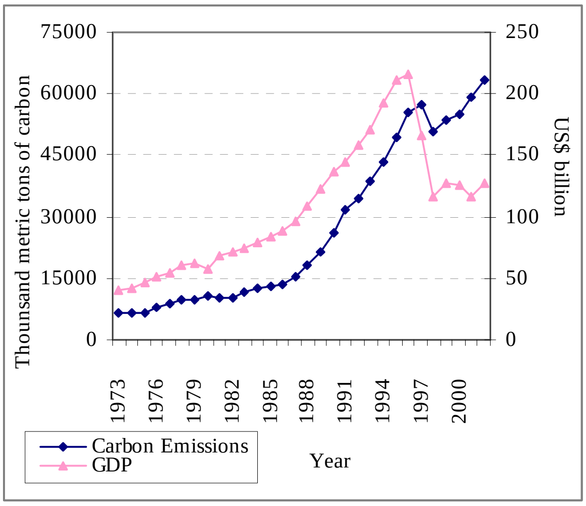

Fig.3. Carbon emissions and economic growth [5], [11]

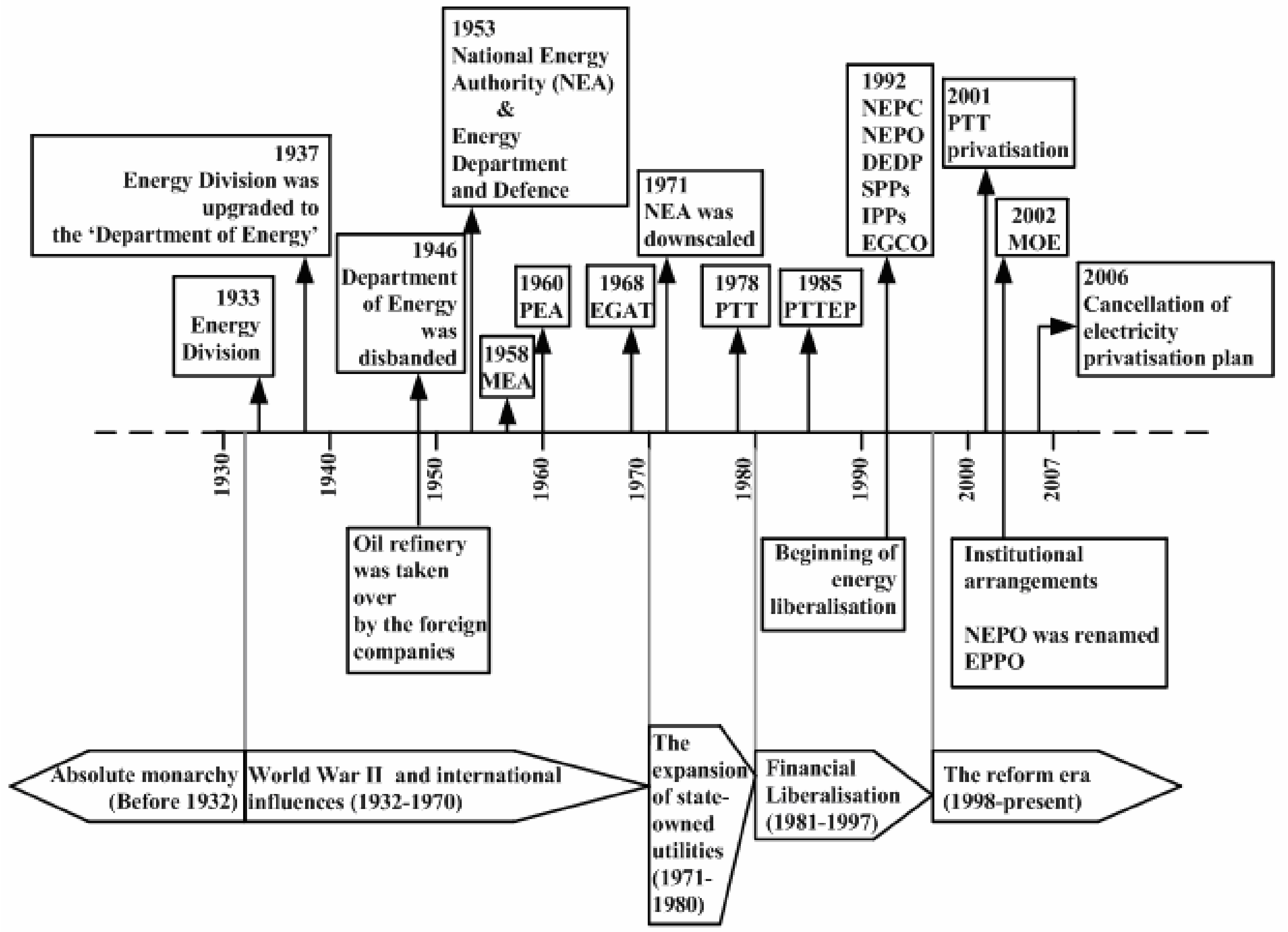

Fig.4. The evolution of Thai energy policy institutions

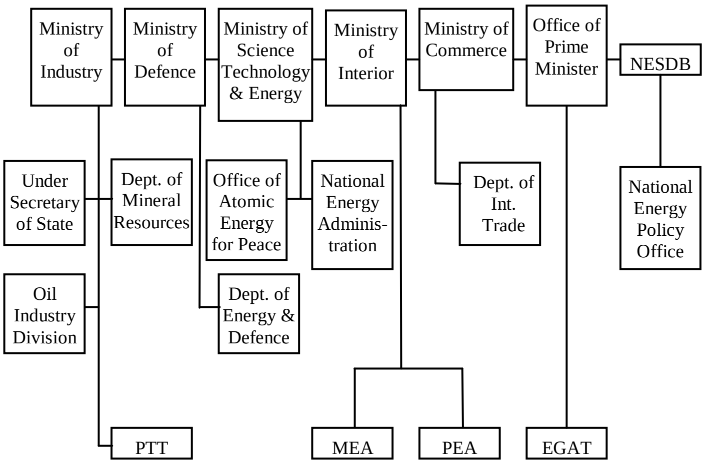

Fig. 5. The structure of energy institutions in the 1980s [21]

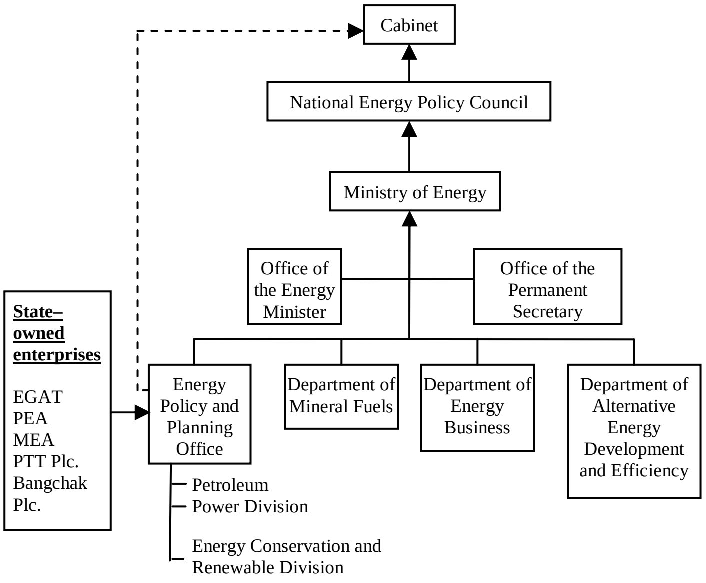

Fig. 6. The current energy institutions [6], [17]

The conflicts between institutions became an issue. According to [17], 'In theory it was the responsibility of the NEA to regulate the utilities. … The utilities refused to share key information with the NEA which would have allowed the NEA to effectively serve as a regulatory body. As it became clear that the NEA lacked data, analytical capability, and enforcement authority, the NEA became simply an energy data collection agency and also the agency entrusted with energy efficiency and renewable energy'. Therefore, NEA lost political power as well because it lacked a clear area of responsibility.

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Financial liberalisation (1981-1997)

The importance of energy in achieving economic growth emerged as an issue in the 1980s, when energy demand increased rapidly due to industrialisation and urbanisation of the country. According to [20], 'The 1980s were a period of structural adjustment and industrial take-off… the economic boom was largely export driven, especially the latter half of the 1980s. Consequently, the country's economic structure changed,… the industrial sector accounted for about 30% of GDP in the 1980s'. During these years, Thailand began to notice the impact of inefficient energy policies and institutions, for example, the impacts caused by the

1979 energy crisis and the 1990 gulf war. To improve the efficiency of country's energy system required significant energy investments. In order to attract these investments, Thailand decided to liberalise its energy industry. In 1985, the PTT Exploration Production (PTTEP) was established, responsible to explore petroleum resources within and across the country. PTT was restructured in the year 1992, on the basis of recommendations made by McKinsey & Company Inc. As a result, PTT improved its performance as a commercial entity. As part of institution evolution, the National Energy Policy Council (NEPC) and the National Energy Policy Office (NEPO) were established in the year 1992, to be the national energy policy institutions instead of NEA. NEA was renamed Department of Energy Development and Promotion (DEDP). In the same year, the government began the electricity reform. The Small Power Producer (SPP) and the Independent Power Producer (IPP) programs appeared as the first step in this reform. The Electricity Generating Company (EGCO) was created as a subsidiary company of EGAT, purchasing electricity from SPPs and IPPs. The privatisation plans for MEA, PEA and EGAT were announced. They were however fiercely opposed by the labour unions of the state electric utilities. As a result, the electricity privatisation was postponed and no significant changes in the electricity industry occurred during the second half of the 1990s.

The reform era (1998-present)

The impacts of the East Asian financial crisis (1997/98) brought the institutional issues to the fore. As Thailand is an energy-importing country, evidently the energy sectors were strongly impacted by the financial crisis (see, Figure 2). This economic crisis was one of the factors to stimulate the energy industry for further reform. The significant debt due to past infrastructure borrowings and their poor performance also induced Thailand to privatise its energy sector. As a result, in the administration of Prime Minister Thaksin Shinawatra (in office 2001-2006), the government policies focused on economic and energy industry reforms. The government made several institutional arrangements with the principle objective of improving the efficiency of institutions. Several organisations were established in order to centralise the formulation and implementation of the country's policy. The Ministry of Energy (MOE) was established in 2002, under the Administrative Organisation of State Affairs Act (No.5) BE. 2545 (2002). More than 20 government agencies, in 9 ministries and state-owned enterprises, responsible for energy planning policy, regulation and implementation were unified. The supervision role of NEPO was transferred from the secretariat of the Prime Minister to the Ministry of Energy. NEPO was renamed the Energy Planning and Policy Office (EPPO). In the year 2001, NEPO approved the partial listing of PTT. PTT was privatised and became PTT Plc., listed on the Stock Exchange of Thailand. For the electricity industry, in the year 2003, EGAT was approved by the cabinet to be corporatised as a public company under the Corporation Law. However the plan to list EGAT on the Stock Exchange was cancelled in 2006 by Thailand's Supreme Administrative Court.

4. A REVIEW OF ENERGY POLICIES

Since 1932, the main focus of Thai energy policies has been to reduce the country's dependence on imports, especially oil imports. Indigenous oil production and diversification of fuel resources therefore received considerable policy attention. However, there were no consistent and coherent energy policies to achieve these objectives until 1992. After the establishment of NEPC and NEPO, the central energy agencies, several energy policies were formulated. This section reviews major energy policies that were approved by the NEPO (EPPO), under the National Energy Policy Council Act BE 2535 (1992).

Policies on privatisation and liberalisation

The policies on energy industry privatisation in Thailand began to be formulated in 1992, with the aim to develop the energy sector, primarily to satisfy the growing energy demand and economic expansion. SPP and IPP projects were created to increase private participation in the electricity markets. The 1997 financial crisis and the ensuing rapid economic slow-down forced Thailand to accept the conditions associated with the economic adjustment package offered by the IMF. This prompted the Thai government to accelerate the energy reform program. In September 2001, NEPO approved the privatisation plan of PTT, the state-owned oil and gas enterprise. Thus, PTT became PTT Plc. For the electricity industry, EGAT was slated to be corporatised in the year 2003 as a public company under the Corporation Law. However, the privatisation plans were cancelled by the Supreme Administrative Court in the year 2006 due to the political and societal opposition. According to [22], reasons of this cancellation were, '…the conflicts of interest plaguing the information of the committee that worked on the state agency corporatisation process; the conflict of interest in the appointment of a chairman for the public hearing committee and the improper process of the hearings; and the fact that EGAT would still have held state power of land expropriation after being privatised'.

Policies on energy conservation

The main objectives of the Energy Conservation Promotion Act BE 2535 (1992) are to promote energy conservation and encourage investment in energy savings in the factories and buildings as specified by the law. Under this Act, financial support is available for the projects that improve efficiency of energy consumption. Thailand has already implemented two phases of energy conservation programs. The first phase was in the period 1995-1999 and the second phase 2000-2004. Thailand is now implementing the third phase of energy conservation program (2005-2011). The past and existing conservation policies are summarised as follow:

- *The first phase (1995-1999)*

The policies during this period can be divided into three categorises, namely, compulsory, voluntary, and complementary. The compulsory program includes the financial support for the development of energy efficiency improvement in the existing factories and commercial buildings. The voluntary program focuses on research and development projects in the area of energy saving potential, technologies, and policy. The increased competency of human resources and public campaigns are emphasised in the complementary program. The total expenditure in the first phase on these programs was $195 million. The total value of energy saving over the period 1995-1999 was $203 million.

- *The second phase (2000-2004)*

This phase continued the conservation programs from the first phase. The compulsory, voluntary and complementary programs remained. Renewed effort was devoted in this phase to promote the energy conservation plans among various groups in society. The total expenditure used in this period was $396 million, nearly double the expenditure in the first phase. The total value of energy saving were estimated to be $334 million over the 4-year period.

- *The third phase (2005-2011)*

The energy conservation policies in the current phase can be divided into three main parts, namely, the renewable energy development program, energy efficiency program, and the analysis of energy strategies program. This phase expects to result in a decrease in energy consumption for producing one unit of GDP from 1.4 to 1 and increase in the share of renewable energy to 8% of total primary energy by the year 2011.

Policies on international energy cooperation

Thailand is a participant in several regional energy programs, for example, the ASEAN and GMS energy cooperation programs. The electricity demand in Thailand is forecasted to reach 49,975 MW in the year 2020, which is almost double when compared to the electricity demand in the year 2006 (25,371 MW) [23]. In order to meet the future demand, the expansion of the electricity industry is necessary. This might create several issues relating, for example, to investment, environment, public health, and livelihood of people. However, the increase in imported energy supply from neighbouring countries could meet increased electricity demand in Thailand [24]. The ASEAN 2020 Vision adopted in 1997 by the heads of state at the 2nd ASEAN Informal Summit envisioned an energy-interconnected South-east Asia through the ASEAN Power Grid and the Trans-ASEAN Gas Pipeline Projects. These ventures call for regional cooperation in power pooling and maximising efficient use of energy resources [25]. Thailand is a strong supporter of the Power Grid project in ASEAN, especially the construction of hydro-electric dams in Myanmar and Laos. This is disturbing because this could place environmental and humanitarian strains on Myanmar and Laos where environmental laws are less stringent as compared to Thailand [25]. According to [26], '…in the future, Thailand will be the main buyer of hydro-electricity from the neighbouring countries and will act as a middleman, selling power to the other nations'.

The foregoing review of the existing energy policies suggests that while these policies are well intentioned, they are insular, narrowly focused and lacking in concerns about their economy-wide impacts. Moreover, there may be some inherent conflicts among various policies. For example, while the privatisation and liberalisation policies could attract energy investments, they might raise issues of sovereignty. The energy conservation policies, while useful, may not be able to meet the rapidly rising energy demand. Moreover, the rising economic prosperity might militate against the adoption of meaningful energy conservation programs. Further, increased energy cooperation policies could ensure energy security but might affect sovereignty. Some of the above noted anomalies could be traced to the fragmented nature of decision-making and planning and policy development processes. For example, there is no apex body that has the overall responsibility for providing strategic direction for policy development, its implementation, feedback, and refinement. Even the modelling approaches followed by the energy planning agency (namely, EPPO) appear to be essentially technocratic, bottom-up, and devoid of economic linkages. Against this backdrop, this paper argues that the current energy policies are unlikely to be able to provide a satisfactory redress to the energy challenges facing Thailand.

5. A WAY FORWARD

A possible way forward is to develop a "policy coherence". This would entail changes in the current policy settings, involving changes to the planning philosophies, institutions and implementation practices. The energy planning philosophy would need to clearly articulate its link with the broader economic, environmental and social policy regimes – with full recognition of the socio-political realities of Thailand. Such articulation could be assisted, for example, through the development of a comprehensive modelling and policy analysis framework that allows integration between technical, economic, environmental and social realms of energy development – and more importantly - provides a justifiable mechanism for the reconciliation of conflicts that are inevitable in such policy setting. The development of such a framework constitutes the current focus of these authors' research.

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Optimal PMU Placement by Stochastic Simulated Annealing for Power System State Estimation

Thawatch Kerdchuen and Weerakorn Ongsakul

Abstract— *This paper proposes stochastic simulated annealing (SSA) for solving optimal phasor measurement unit (PMU) placement in the power system for state estimation. The placement of PMU is used to detect bad data. The critical measurement free system can detect any single measurement bad data. Critical measurement identification is included as a penalty function. The topologically observable concept is used to check observability. Total cost of SSA is less than hybrid genetic algorithm and simulated annealing (HGS) especially in the large systems.*

Keywords— **Power system state estimation, Stochastic simulated annealing, Observability, PMU placement.**

1. INTRODUCTION

The rapid growth of computer and communication technology is challenging to power system monitoring and control. All phasor measurement units (PMUs) in power system might be synchronized either by satellite or fiber optic systems. PMU can measure bus voltage magnitude, bus voltage phase angle and real and reactive current flow in the incident lines [1]. Conventional power system state estimation uses power flow and injection measurements connected via remote terminal unit (RTU) to control centre. Then, nonlinear state estimator in energy management system (EMS) is processed. If PMU is used, linear power system state estimation can be used [2, 3].

So far, a few PMU is placed to enable bad data detection [1]. In power system with conventional measurement, bad data is detected by additional PMU. Power system state estimation with bad data detection is satisfied for the measurement system without critical measurement. Critical measurement is identified by Peters-Wilkinson method [1]. However, several methods are introduced for critical measurement identification [4, 5]. In [4], critical measurement is easily identified by residual analysis. In [6], the entire measurement system for state estimation is connected via several PMUs but bad data detection is not considered. In [4], bad data detection is considered for optimal measurement placement. Remote terminal unit (RTU) with conventional measurement is placed by genetic algorithm (GA). Residual analysis is used to identify the critical measurement.

In this paper, optimal PMU placement is proposed for state estimation. Critical measurement identification by residual analysis is included in the cost function of SSA and hybrid GA and SA (HGS) [9]. The “0” and “1” at system bus are coding for PMU placement. The topologically observable concept is used to check observability. This observability concept is easily observed that all buses are connected by a single connected graph. Results are shown both only system observable and observable considering critical measurement free.

2. FUNDAMENTAL OF PMU PLACEMENT

PMU placement is generally required to make the system observable. Moreover, the reliable measurement system is required such as bad data. Critical measurement free is necessary for bad data detection in any measurement.

Measurement Jacobian with PMU for Observability Analysis

The linear model for real power and bus phase angles of conventional state estimation are expressed in following form

$$\mathbf{z}_P = \mathbf{H}_{P\delta}\boldsymbol{\delta} + e_P \qquad (1)$$

where

$\mathbf{z}_P$	real power measurement vector of real power flow and injection measurements
$\boldsymbol{\delta}$	bus phase angle vector
$\mathbf{H}_{P\delta}$	measurement Jacobian matrix for real power measurements versus all bus voltage angles
$\mathbf{e}_P$	real power measurement error vector.

PMU can measure both voltage phasor of its own bus and current phasors on incident branches. This typical measuring configuration is shown in Figure 1.

In Figure 1, a PMU is installed at bus B, thus a bus voltage phasor and three current phasors are measured. Each incident branch, the current phasor measurement between buses i and j can be written in rectangular coordinates as shown in Figure 2, where y and y_{sh} are defined as series admittance and shunt admittance respectively.

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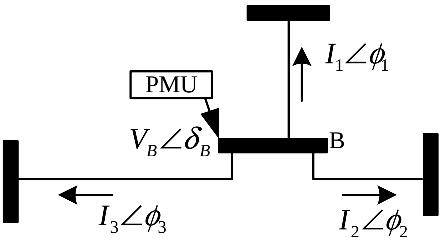


Fig. 1. Phasor measurements by a PMU

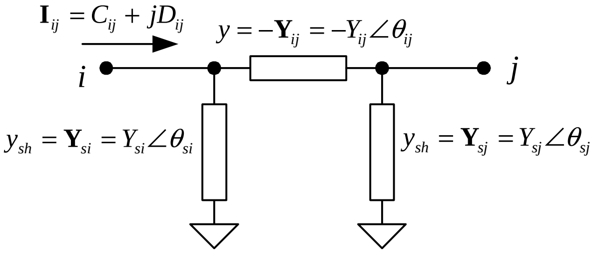


Fig. 2. Transmission line model

The expressions C_{ij} and D_{ij} are

$$C_{ij} = V_iY_{si}\cos(\delta_i+\theta_{si}) + V_jY_{ij}\cos(\delta_j+\theta_{ij}) - V_iY_{ij}\cos(\delta_i+\theta_{ij}) \quad (2)$$

$$D_{ij} = V_iY_{si}\sin(\delta_i+\theta_{si}) + V_jY_{ij}\sin(\delta_j+\theta_{ij}) - V_iY_{ij}\sin(\delta_i+\theta_{ij}) \quad (3)$$

The power system state vector is given as $\mathbf{x} = \left[V_1\ V_2 ... V_n\ \delta_1\ \delta_2 ... \delta_n\right]^T$. Thus, the entries of measurement Jacobian $\mathbf{H}$ corresponding to the real and reactive parts of current phasors are:

$$\frac{\partial C_{ij}}{\partial V_i} = Y_{si}\cos(\delta_i+\theta_{si}) - Y_{ij}\cos(\delta_i+\theta_{ij})$$

$$\frac{\partial C_{ij}}{\partial V_j} = Y_{ij}\cos(\delta_i+\theta_{ij})$$

$$\frac{\partial C_{ij}}{\partial \delta_i} = -V_iY_{si}\sin(\delta_i+\theta_{si}) + V_iY_{ij}\sin(\delta_i+\theta_{ij}) \quad (4)$$

$$\frac{\partial C_{ij}}{\partial \delta_j} = -V_jY_{ij}\sin(\delta_j+\theta_{ij}) \quad (5)$$

$$\frac{\partial D_{ij}}{\partial V_i} = Y_{si}\sin(\delta_i+\theta_{si}) - Y_{ij}\sin(\delta_i+\theta_{ij})$$

$$\frac{\partial D_{ij}}{\partial V_j} = Y_{ij}\sin(\delta_i+\theta_{ij})$$

$$\frac{\partial D_{ij}}{\partial \delta_i} = V_iY_{si}\cos(\delta_i+\theta_{si}) + V_iY_{ij}\cos(\delta_i+\theta_{ij}) \quad (6)$$

$$\frac{\partial D_{ij}}{\partial \delta_j} = V_jY_{ij}\cos(\delta_j+\theta_{ij}) \quad (7)$$

The system states are estimated if the measurement system is observable. Since the observability is independent to the branch parameter, all branch impedances are assumed as j1.0 p.u., and all bus voltages are assumed as 1.0 p.u. Based on (4) to (7) and the assumption of impedances and voltages, thus the real part of current phasor can be written as

$$real(\mathbf{I}_{ij}) = \delta_i - \delta_j$$

Therefore, the linear model measurement Jacobian $\mathbf{H}_{P\delta}$ in (1) when PMU installed at bus i can be written as $\mathbf{H}_{I\delta}$

$$\mathbf{H}_{I\delta} = \begin{array}{c|ccccc|} & .. & \delta_i & \delta_j & \delta_k & .. \\ \hline .. & .. & .. & .. & .. & .. \\ \delta_i & .. & 1 & 0 & 0 & .. \\ \mathbf{I}_{ij} & .. & 1 & \text{-}1 & 0 & .. \\ \mathbf{I}_{ik} & .. & 1 & 0 & \text{-}1 & .. \\ .. & .. & .. & .. & .. & .. \end{array}$$

The above measurement Jacobian $\mathbf{H}_{I\delta}$ assumes the installed PMU at bus i and two incident branches. The topological observability is easily introduced to analyze. If all buses are connected by current flow measurement, the system is observable. Similarly, the system is said to be topologically observable if rank of $\mathbf{H}_{I\delta}$ is equal to $N-1$, where N is the number of system buses. In this topologically observable consideration, the row δ_i of $\mathbf{H}_{I\delta}$ should be deleted, since all connected buses are emerged only via current flow measurement.

Critical Measurement Identification

The WLS estimator will minimize the index $J(\mathbf{x})$, defined as follows.

$$J(\mathbf{x}) = (\mathbf{z}-\mathbf{Hx})^T\mathbf{W}(\mathbf{z}-\mathbf{Hx}) \quad (8)$$

Matrix $\mathbf{W}$ is a diagonal matrix whose elements are measurement weight factors. If bad data or gross error occurs in a measurement and makes unable to estimate the system state, measurement is defined as a critical measurement (*cm*). Thus, in case of single measurement can be lost from the power system that means power system is absence of critical measurement. Therefore the absence of critical measurement in power system, bad data in any single measurement pair is detected. In filtering process, the state estimate $\hat{x}$ which minimizes $J(x)$ in (8) can be obtained from:

$$\frac{\partial J}{\partial x} = \mathbf{H}^T\mathbf{W}(\mathbf{z} - \mathbf{H}\hat{\mathbf{x}}) = 0$$

$$\hat{\mathbf{x}} = \mathbf{G}^{-1}\mathbf{H}^T\mathbf{z} \quad (9)$$

where $\mathbf{G} = \mathbf{H}^T\mathbf{H}$ is gain matrix. The residual vector **r**, defined as the difference between **z** and the corresponding filtered quantities $\hat{\mathbf{z}} = \mathbf{H}\hat{\mathbf{x}}$. In a dataset received for processing, the i^{th} measurement is declared critical if:

$$r(i) = z(i) - \hat{z}(i) = 0 \tag{10}$$

$$\sigma_E(i) = \sqrt{E(i,i)} = 0 \tag{11}$$

Using of (9) and (10), the residuals in terms of elements of matrix **E** as follows:

$$\begin{aligned}\mathbf{r} &= \mathbf{z} - \hat{\mathbf{z}} = \mathbf{z} - \mathbf{H}\hat{\mathbf{x}} = \mathbf{z} - \mathbf{H}(\mathbf{G}^{-1}\mathbf{H}^T\mathbf{z}) \\ &= (\mathbf{I} - \mathbf{H}\mathbf{G}^{-1}\mathbf{H}^T)\mathbf{z} = \mathbf{E}\mathbf{z}\end{aligned} \tag{12}$$

where $\mathbf{E} = \mathbf{I} - \mathbf{H}\mathbf{G}^{-1}\mathbf{H}^T$ and **z** is unity vector (This simplification is based on the fact that *cm* property established from equation (10) to (12) is independently of measurement values). Therefore, the i^{th} component of residual vector is calculated by:

$$r(i) = \sum_{k=1}^{m} E(i,k) \tag{13}$$

For each $z(i)$ of measurement set, if $r(i)$ and $E(i,i)$ are zero, then declare $z(i)$ as critical measurement [4].

3. PMU PLACEMENT PROBLEM FORMULATION

The objective function of optimal PMU placement is to minimize the cost of those PMUs placement in the power system. The number of PMUs is directly dependent on the costs of PMU. Thus, the objective is to minimize the total number of PMUs as follows

$$\text{Min} \quad Cost(N_{PMU}) = \sum_{i=1}^{N_{PMU}} PMU_i \tag{14}$$

subjects to the observability constraints

$$zero\_pivot = 1 \tag{15}$$

or

$$rank(\mathbf{G}_{I\delta}) = N - 1 \tag{16}$$

or

$$rank(\mathbf{H}_{I\delta}) = N - 1 \tag{17}$$

where N_{PMU} is the total number of PMUs, and PMU_i is the i^{th} PMU of entire system. Matrix $\mathbf{G}_{I\delta}$ and $\mathbf{H}_{I\delta}$ in (16) and (17) are related with the terms of current flow measurement of PMU installation. Constraint (15) is used when triangular factorization or numerical method is used for observability analysis. In (13), zero pivot encounters during factorization. Constraints (16) and (17) are used when $P\delta$ observability concept used. Similarly, the system is topologically observable if constraint (17) is satisfied.

Cost evaluation of solution is following to (14) with penalties. Penalties include observability, and critical measurement. However, the minimal penalty part requirement is observability.

$$\text{Min} \quad Cost(N_{PMU}) = N_{PMU} + Penalties \tag{18}$$

$$\begin{aligned}&Penalties = Penalty1 + Penalty2 \\ &Penalty1 = \left[N - 1 - rank(\mathbf{H}_{I\delta})\right](N) \\ &Penalty2 = (\text{No. of } cm)(N)\end{aligned} \tag{19}$$

First penalty is appeared if system is unobservable. The *penalty*2 is occurred if the system is with critical measurement.

4. SSA IMPLEMENTATION

This SSA is derived from adaptive SA with very fast annealing [8]. The important components for optimal PMU placement solving are solution coding and new solution generating.

Solution Coding

Random solution bits of solution coding represent position of PMUs in a power system. For example, the 10-bus system with 12 branches is typical shown in Figure 3.

0 1 0 0 1 1 0 0 1 0

Fig. 3. Typical random bits solution of 10-bus system for SSA initialization.

In Figure 3, PMUs are installed at buses 2, 5, 6 and 9. These solution bits are used to form measurement Jacobian $\mathbf{H}_{I\delta}$. Then, cost function in (18) is evaluated.

New Solution Generating

Initial solution is perturbed to generate new solution. Perturbing method of SSA uses bit flipping and bit exchanging. Fifty percent probability is applied between bit flipping and bit exchanging. Position for bit flipping and positions for bit exchanging are randomly generated. Perturbing method is shown in Figure 4.

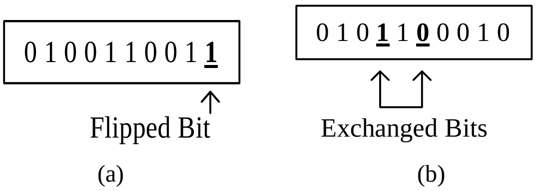


Fig. 4. Typical new solution creating (a) bit flipping (b) bit exchanging.

SSA Process

SSA process for solving optimal PMU placement is shown as follows:

```
Step 1: The solution is randomly initialized ($XInt$), also initial temperature $T_0 = 50$ and temperature length $T_L = N$.
Step 2: Solution evaluation of initial solution ($CostInt$) using (18), set old solution $Xold = XInt$, set best solution $Xb = XInt$ and set old best cost $Bold = CostInt$.
Step 3: Set iteration $k = 1$, set maximum evaluation step $maxstep = 400$ and the same result counter $S = 0$
Step 4: If $k \le maxstep$ and $S \le 100$, set sub-iteration $k_1 = 1$. Otherwise go to Step 5.
    Step 4.1: If $k_1 \le T_L$. Otherwise go to Step 4.2
        Step 4.1.1: the new solution ($Xnew$) is created by the $Xold$ perturbing
        Step 4.1.2: $Xnew$ cost evaluation
        Step 4.1.3: if $Xnew$ cost $\le$ $Xold$ cost, $Xold = Xnew$ and $Xb = Xnew$. Else if $e^{(Xold\ \mathrm{cost} - Xnew\ \mathrm{cost})/T} > rand$, $Xold = Xnew$. Otherwise $Xold = Xold$.
        Step 4.1.4: Set $k_1 = k_1 + 1$ and return to Step 4.1
    Step 4.2: update temperature $T = T_0 e^{(-ck^q)}$ [8], where $c = 2e^{(-\log(maxstep)/bits)}$, $q$ is quenching factor, 0.5, and $bits$ is number of solution bits
    Step 4.3: If $Bold = Xb$, $S = S + 1$. Otherwise $S = 0$.
    Step 4.4: Set $Bold = Xb$.
    Step 4.5: Set $k = k + 1$, return to Step 4.
Step 5: The best solution is $Xb$
```

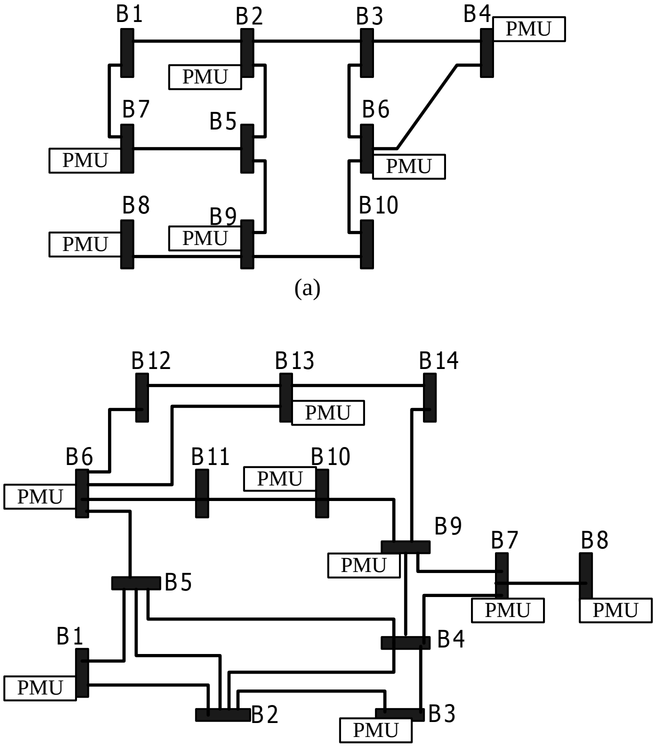
This solution updating Step 4.1.3 makes the diversity of solution, and the new direction of search shall be addressed by new solution generating. Temperature length is defined by the number of solution bits. However if we need to reduce the computing time, temperature length can be decreased.

5. NUMERICAL RESULTS

The total number of PMUs and their locations whether with observable or observable with critical measurement free are given in Table 1. To compare, HGS [9] is also used to solve optimal PMU placement. HGS is based on GA that uses SA acceptance criterion for chromosome selection. Population size, crossover and mutation probabilities are determined by experiments. Numerical results by SSA and HGS are shown in Table 1. Also the typical PMU placements are shown in Figure 5.

Table 1. Numerical PMU placement in several systems

System	Number of PMUs			
	Observable		Observable without *cm*	
	HGS	SA	HGS	SA
10-bus	4	4	6	6
IEEE 14-bus	4	4	8	8
IEEE 30-bus	10	10	18	18
IEEE 57-bus	20	19	29	28
IEEE 118-bus	36	34	65	63



(a)

(b)

Fig. 5. Typical optimal PMU placement with *cm* free for (a) 10-bus system (b) IEEE 14-bus system

In Table 1, the number of PMU for making the observable system is less than that for making the observable system with critical measurement free. For critical measurement free, any single flow current measurement of PMU can be lost while the system is still observable. Therefore, the number of PMUs is higher considering only observable system condition.

6. CONCLUSION

Optimal PMU is placed in power system for power system state estimation. Critical measurement free is included for bad data in any single measurement detection ability. SA with stochastic new solution generating is introduced as SSA. SSA result has indicated that the number of PMUs and placement sites are lower than HGS, leading to investment cost savings.

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Control of Single Phase PWM Converter for Renewable Energy System Using Active and Reactive Current Components

S. Wangsathitwong, S. Sirisumrannukul, S. Chatratana and W. Deleroi

Abstract**—** *This paper presents a control of single-phase PWM power converter based on active and reactive current components. In this control scheme, the active power and reactive power can be directly and independently controlled. The line current phasor is decomposed into active and reactive current components, which are in phase and quadrate to the system voltage phasor, respectively. Therefore, two control loops, one for the dc link voltage or active power control and the other for reactive power control, can be formed. Feed forward technique is employed to decouple two control loops and a standard PI controller can be used in each loop effectively. With reactive power control the proposed system can be used to perform as voltage regulation. The performances of the proposed control were simulated and illustrated for rectifying mode, inverting mode and load voltage regulation mode.*

Keywords**— Single-phase PWM converter, Active current and reactive current components, Decoupled control, PI controller.**

1. INTRODUCTION

Renewable energy sources such as wind energy (WE) and photovoltaic (PV) system are widely used and their installed capacities are dramatically increased every year. These systems require power electronic converter to control the energy transfer, whether they are isolated or grid connected. Both WE and PV can be operated as an individual system or a hybrid system. When a system is connected to the electric supply, the converter must be able to handle bi-directional flow of the active and reactive power of the converter, i.e. the rectifying and inverting modes of operation.

For three-phase system, the model of the converter is based on d-q synchronously rotating reference frame [1], [2]. In this frame, the three-phase ac voltages and currents are transferred onto the d-q axis, which is oriented along the supply voltage vector. The active power and reactive power are decoupled and the power flow between ac supply and the dc link can be independently controlled to flow in both directions.

For small renewable energy systems that are installed in rural or remote areas, the supply side converter may be of single-phase type. The supply side converter is controlled to maintain constant dc link voltage and to produce ac sinusoidal current waveform at the point of common coupling (PCC). The ac current reference is derived from 50 Hz sinusoidal voltage waveform and a current controller is required to track the reference waveform. Normally, the current control scheme is based on hysteresis control [3]. This controller is simple and robust but there are several disadvantages such as variable switching frequency, current error band and high frequency limit [4]. Furthermore, due to the ac sinusoidal reference current waveform, the design of the PI controller for this signal is not as simple as the design with dc constant reference signal.

This paper proposes a control method for a single phase PWM converter. The method is based on active current and reactive current components. These two components are derived from the ac line current. The active current component is a sinusoidal ac current which is in phase with the supply voltage. The reactive current component is a sinusoidal ac current which is in quadrature with the supply voltage. At steady state, the magnitudes of these current components are constant. Consequently, the single phase PWM converter can be controlled in the similar fashion to the control of three-phase PWM converter system based on the d-q axis. The operation with this control scheme leads to a linear control design technique and a simple design of input filter with a specified high switching frequency.

With reactive power control, the proposed control technique can be used as a voltage sag compensator. If the voltage at the point of common coupling (PCC) drops below a specified value, the reactive power flow into the ac system will be increased and the PCC voltage will be restored.

This paper is organized in four parts. The mathematical model of a single phase PWM converter based on active and reactive current components is described in Section 2.1. In Section 2.2, the linearized model is analyzed to determine system stability. The method to compensate voltage sag is described in Section 2.3. The simulation results are shown in Section 3 for rectifying mode, inverting mode and voltage sag compensation mode. The conclusion is given in Section 4.

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2. SYSTEM CONFIGURATION AND MODELING

2.1 Nonlinear Model Analysis

The single phase PWM converter is a H-bridge converter connected to the electric supply with a dc capacitor on the dc side. The simplified model is depicted in Figure 1. The supply voltage and dc power equations for the PWM converter are given in (1) and (2).

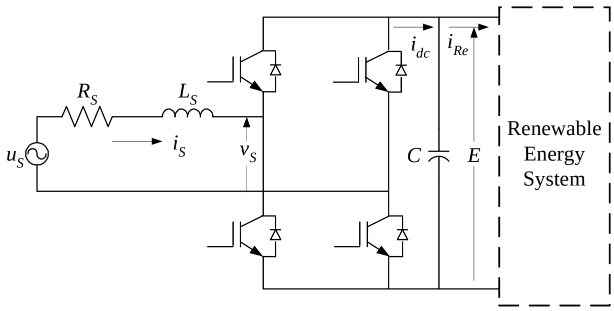

Fig.1. Single-Phase PWM Converter

$$u_S = R_S i_S + L_S \frac{di_S}{dt} + v_S \tag{1}$$

$$Ei_{Re} + EC\frac{dE}{dt} = Ei_{dc} = P_{dc} \tag{2}$$

By assigning the supply voltage, u_S, as a reference, the instantaneous values of u_S , i_S and v_S can be expressed as

$$u_S = U_S \sin(wt) \tag{3}$$

$$i_S = I_S \sin(wt - q) \tag{4}$$

$$v_S = V_S \sin(wt - d) \tag{5}$$

The expressions for, i_S and v_S, can be expanded into two terms as

$$i_S = I_{Sp} \sin(wt) + I_{Sq} \cos(wt) \tag{6}$$

$$v_S = V_{Sp} \sin(wt) + V_{Sq} \cos(wt) \tag{7}$$

where the active and reactive components of the currents *(* I_{sp}, I_{sq}*)* and voltages *(*V_{sp}, V_{sq}*)* are

$$I_{Sp} = I_S \cos(q), \quad I_{Sq} = -I_S \sin(q)$$

$$V_{Sp} = V_S \cos(d), \quad V_{Sq} = -V_S \sin(d)$$

The average single phase ac active power and reactive power flow are

$$P = \frac{1}{2}U_S I_{Sp} \tag{8}$$

$$Q = -\frac{1}{2}U_S I_{Sq} \tag{9}$$

Substituting (6) and (7) in (1) and separating the coefficient of $\sin(\omega t)$ into one equation and the coefficient of $\cos(\omega t)$ into another equation, the two equations can then be expressed as

$$R_S I_{Sp} + L_S \frac{dI_{Sp}}{dt} = U_S + wL_S I_{Sq} - V_{Sp} \tag{10}$$

$$R_S I_{Sq} + L_S \frac{dI_{Sq}}{dt} = -wL_S I_{Sp} - V_{Sq} \tag{11}$$

If the power loss in the converter is small and can be neglected, the dc power in (2) is equal to the ac active power in (8), i.e.

$$Ei_{Re} + EC\frac{dE}{dt} = \frac{1}{2}U_S I_{Sp} \tag{12}$$

Apparently, the active current component can be used to regulate dc voltage and the reactive current component can be used to regulate the reactive power.

The block diagram of the proposed PWM converter control is shown in Figure 2, with the selection of V_{PCC} control and reactive current control. The control objective in Figure 2 is to maintain the dc link voltage (E) at a desired value and the reactive current (I_{sq}^*) at a reference either positive, negative or unity power factor. Some important characteristics of the control loop in Figure 2 are as follows.

1) The voltage of the line is measured and the magnitude U_s and the reference angle ωt are derived.

2) The line current I_s is measured with the help of ωt to obtain active current component I_{sp} and reactive current component I_{sq}. I_{sp} and I_{sq} will be used as feedback signal for current control and as feedforward signal for decoupling process.

3) In the dc voltage control loop, the dc voltage of the capacitor E is measured and fed back for comparison. A PI controller is used to regulate the dc voltage. The active power command P^* from the controller is multiplied by a factor of $2/U_S$ to obtain the active current command I_{sp}^*. The error of the active current command and the actual active current is the input of another PI controller. The feed forward signal of $\omega L_s I_{sq}$ is added to the output of the controller to decouple the reactive component from the active equation. The supply voltage is then added to obtain the active voltage component command V_{sq}^*.

4) Similar reasoning can be used to describe the signal flow in the reactive current loop.

5) The active voltage command, reactive voltage command and the reference angle of the voltage from the measurement are the inputs for the PWM controller.

6) The PWM controller generates switching signals for the converter.

2.2 Linearized Model and Stability Analysis

The nonlinear equation in (9)-(12) can be linearized [5] and the linear control analysis such as stability and design technique can be directly applied. The linear relation between converter terminal voltage, v_S, and dc bus voltage, E, is expressed as

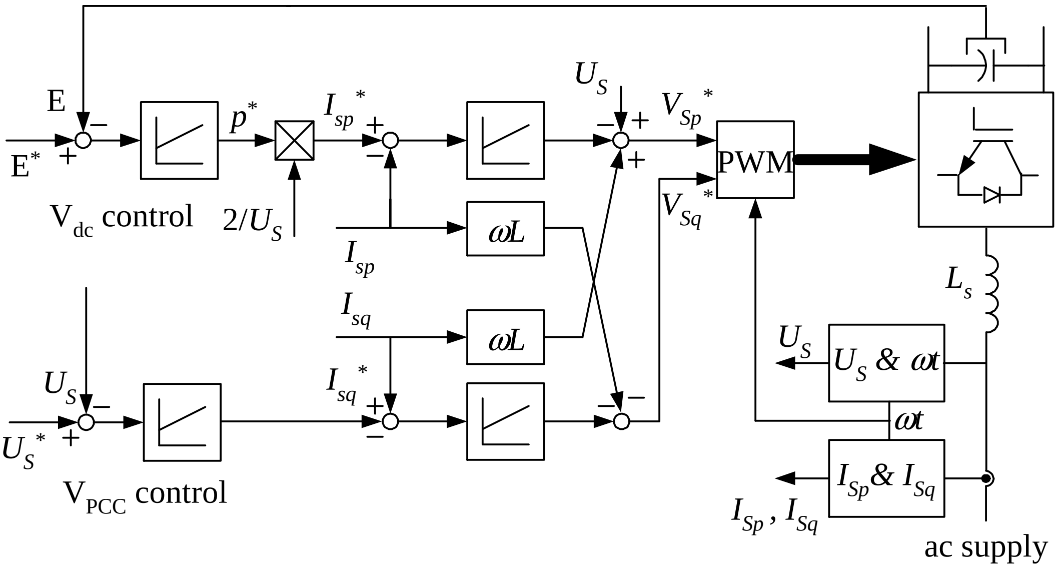

Fig.2. Control Block Diagram of Active and Reactive Current Component of PWM Converter

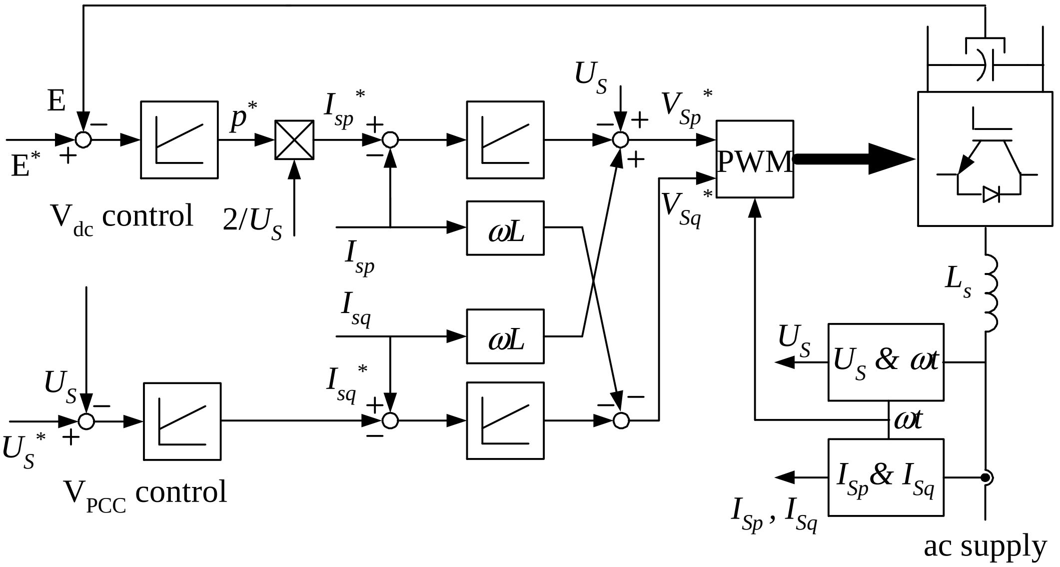

Fig.2. Control Block Diagram of Active and Reactive Current Component of PWM Converter

$$v_S = mE \tag{13}$$

Equations (10)-(12) can then be rewritten in state equation form as follows.

$$L_S \frac{dI_{Sp}}{dt} = -R_S I_{Sp} + wL_S I_{Sq} + (U_S - V_{Sp}) \tag{14}$$

$$L_S \frac{dI_{Sq}}{dt} = -R_S I_{Sq} - wL_S I_{Sp} - V_{Sq} \tag{15}$$

$$C\frac{dE}{dt} = i_{dc} - \frac{E}{R_{dc}} \tag{16}$$

If it is assumed that the dc power is equal to converter terminal active power, the expression for the dc power is

$$P_{dc} = Ei_{dc} = \frac{1}{2}(V_{Sp}I_{Sp} + V_{Sq}I_{Sq})$$

$$P_{dc} = \frac{1}{2}V_S(I_{Sp}\cos d - I_{Sq}\sin d) \tag{17}$$

$$\frac{v_S}{m}i_{dc} = \frac{1}{2}V_S(I_{Sp}\cos d - I_{Sq}\sin d)$$

$$i_{dc} = \frac{1}{2}m(I_{Sp}\cos d - I_{Sq}\sin d) \tag{18}$$

Substituting (18) in (16), and rearranging (14) – (16) in the standard form results in

$$\frac{d}{dt}\begin{bmatrix} I_{Sp}\\ I_{Sq}\\ E\end{bmatrix} = \begin{bmatrix} -\frac{1}{T_S} & \omega & -\frac{m}{L_S}\cos\delta \\ -\omega & -\frac{1}{T_S} & \frac{m}{L_S}\sin\delta \\ \frac{m}{2C}\cos\delta & -\frac{m}{2C}\sin\delta & -\frac{1}{T_{dc}}\end{bmatrix}\begin{bmatrix}I_{Sp}\\ I_{Sq}\\ E\end{bmatrix} + \begin{bmatrix}\frac{1}{L} & 0\\ 0 & \frac{1}{L}\\ 0 & 0\end{bmatrix}\begin{bmatrix}U_S\\ 0\end{bmatrix} \tag{19}$$

$$\begin{aligned}\frac{d}{dt}\begin{bmatrix} \Delta I_{Sp}\\ \Delta I_{Sq}\\ \Delta E\end{bmatrix} &= \begin{bmatrix} -\frac{1}{T_S} & \omega & -\frac{m_0}{L_S}\cos\delta_0 \\ -\omega & -\frac{1}{T_S} & \frac{m}{L_S}\sin\delta_0 \\ \frac{1}{2}\frac{m_0}{C}\cos\delta_0 & -\frac{1}{2}\frac{m_0}{C}\sin\delta_0 & -\frac{1}{T_{dc}}\end{bmatrix}\begin{bmatrix}\Delta I_{Sp}\\ \Delta I_{Sq}\\ \Delta E\end{bmatrix} \\ &+ \begin{bmatrix} \frac{m_0 E_0}{L_S}\sin\delta_0 & -\frac{E_0}{L_S}\cos\delta_0 \\ \frac{m_0 E_0}{L_S}\cos\delta_0 & \frac{E_0}{L_S}\sin\delta_0 \\ -\frac{1}{2}\frac{m_0}{C}\left(I_{Sp0}\cos\delta_0 + I_{Sq0}\sin\delta_0\right) & \frac{1}{2C}\left(I_{Sp0}\cos\delta_0 - I_{Sq0}\sin\delta_0\right)\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta m\end{bmatrix}\end{aligned} \tag{20}$$

where

$$T_S = \frac{L_S}{R_S} \text{ and } T_{dc} = R_{dc}C$$

The linearization for small perturbation is represented by the first order terms of Taylor's expansion given in (19). The linear difference equations are given in (20). Therefore, the characteristic equation is

$$\begin{aligned}&\lambda^3 + \left(\frac{2}{T_S} + \frac{1}{T_{dc}}\right)\lambda^2 + \left(\frac{2}{T_S T_{dc}} + \frac{1}{T_S^2} + K + \omega^2\right)\lambda \\ &+ \left(\frac{2}{T_S^2 T_{dc}} + \frac{K}{T_S} + \frac{\omega^2}{T_{dc}}\right) = 0\end{aligned} \tag{21}$$

where $K = \frac{1}{2}\frac{m_0^2}{L_S C}$.

In (21), there is no δ term in the characteristic equation. Thus, switching angle does not affect the position of characteristic roots. Reassigning the coefficients of the polynomial in terms of a_0, a_1 an a_2, (21) can be rewritten as

$$l^3 + a_2 l^2 + a_1 l + a_0 = 0$$

The Routh-Hurwitz criterion can be used to determine stability analysis of this system.

$$\begin{array}{l|ll} l^3 & 1 & a_1 \\ l^2 & a_2 & a_0 \\ l^1 & a_1 - \frac{a_0}{a_2} & \\ l^0 & a_0 & \end{array}$$

For the system to be stable, the component of Routh array in the λ^1 row must be greater than 0, which results in

$$\frac{4}{T_S} + \frac{2}{T_{dc}} + \frac{2T_{dc}}{T_S^2} + KT_{dc} + KT_S + 2\omega^2 T_{dc} \geq 0 \tag{22}$$

Obviously, for all positive values of system parameters the system is stable.

2.3 Voltage Sag Compensation

Voltage sag is a reduction of the voltage magnitude from its nominal value. A PWM converter can be used to reduce the influence of the sag. If the voltage at the point of coupling drops, it can be restored by injecting reactive power into the ac system. The PCC voltage magnitude is

$$|u_S| = U_S \tag{23}$$

The reactive power injected by the PWM converter is given in (9). Therefore, if the PCC voltage is too low, the reactive power should be injected and also the reactive current component should be compensated.

The block diagram of PCC voltage control is shown in Figure 2 with a selection switch that receives an input from the output of the first PI controller (PCC voltage control loop) instead of I_{sq}^*. The reference PCC voltage is compared with the actual line voltage and the error is used as the input of the second PI controller (reactive current control loop). The output of this PI controller is the desired reactive current component, which is fed to the reactive current controller, to restore the PCC voltage back to the reference value.

3. SIMULATION RESULTS

From the control block diagram in Figure 2, the proposed method has been verified by computer simulation for three modes of operation: rectifying mode, inverting mode and voltage sag compensation mode.

3.1 Rectifying Mode

In this operation, the converter is operated in order to regulate the dc link voltage at a fixed value in conjunction with a reactive power control. The results are shown in Figures 3, 4 and 5. The converter was initially operated at zero reactive power or unity power factor. It can be seen in Figure 3 that the line current is in phase with the supply voltage. At time = 2 s, the reactive current component reference was decreased in step from 0 to –1500 var. Apparently, the supply current changed from in phase with the supply voltage to leading position. The active power is rather constant, due to the decoupling control, as shown in Figure 4. In Figure 5, the dc link voltage is oscillated in a narrow range of ±3 V but the average voltage is the same as before at 400 V.

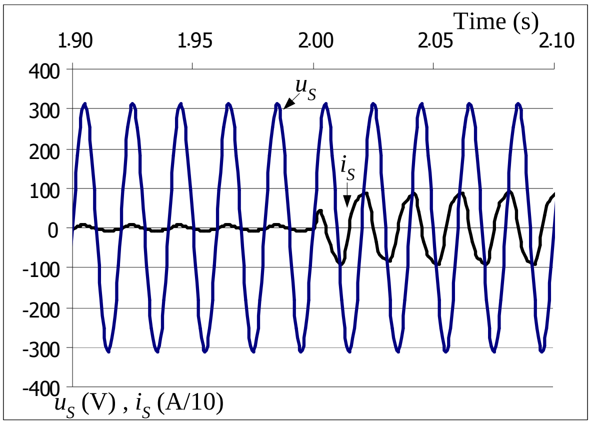

Fig. 3. Supply Voltage and Current

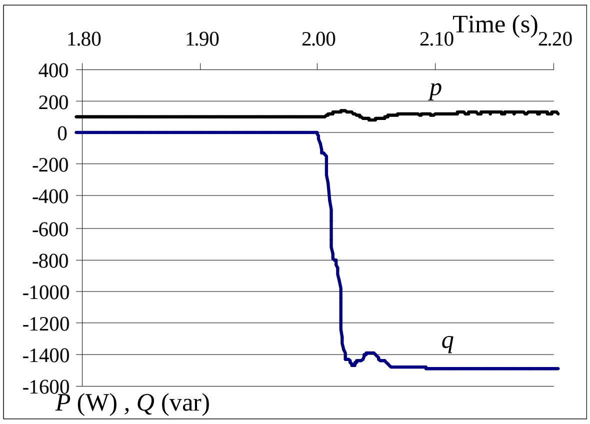

Fig. 4. Active and Reactive Power

3.2 Inverting Mode

When the power flow from the renewable energy system to the dc bus increases, the dc capacitor voltage increases to a value higher than the reference value. The dc voltage controller must regulate the dc voltage by injecting active power to the ac supply network.

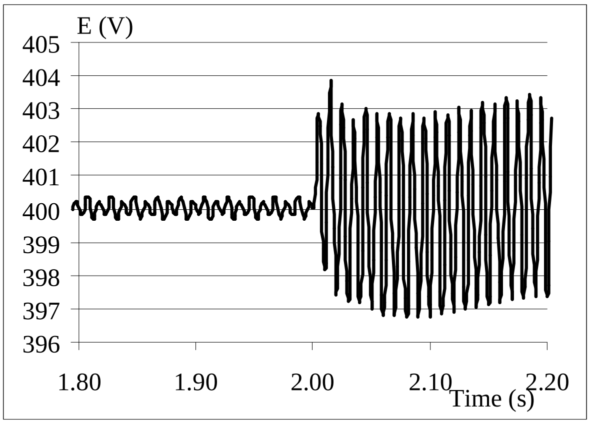

Fig. 5. DC Link Voltage

In Figure 6, the dc voltage was increased from the reference value of 400 V to 402 V at time = 2 s. The dc voltage controller regulated this voltage back to the setting value at 2.3 s.

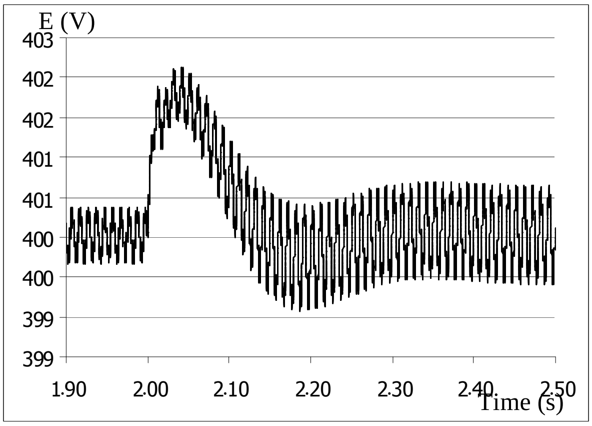

Fig. 6. DC Link Voltage in Inverting Mode

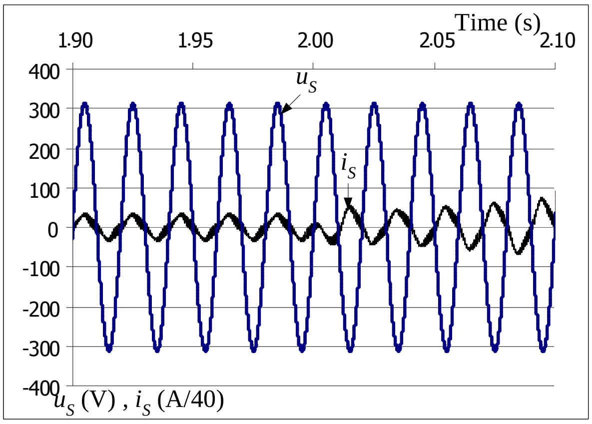

Fig. 7. Supply Voltage and Current in Inverting Mode

In Figure 7, the phase angle difference between the line current and the supply voltage is nearly 180°, which indicates negative power flow. Figure 8 confirms that the active power is negative and energy flows from the converter to the supply while reactive power is still constant.

3.3 Voltage Sag Compensation Mode

In this mode, the reactive current component control loop in Figure 2 is connected to the PCC voltage controller. In Figure 9, when the system voltage was decreased from 1 p.u. to 0.9 p.u. at time = 2 s. The PCC voltage, V_{PCC}, of the system with PCC voltage controlled converter can be restored to a pre-disturbance voltage level of 1 p.u.

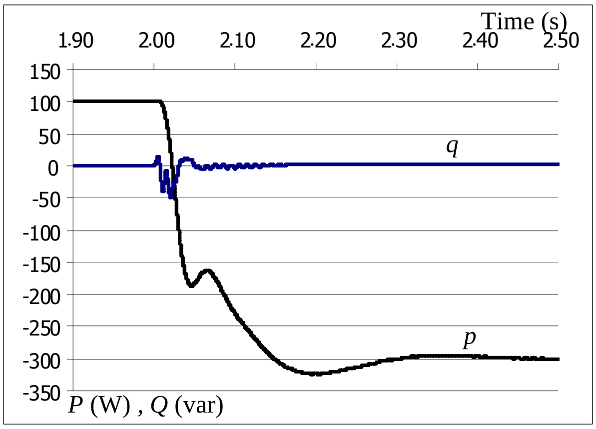

Fig. 8. Active and Reactive Power in Inverting Mode

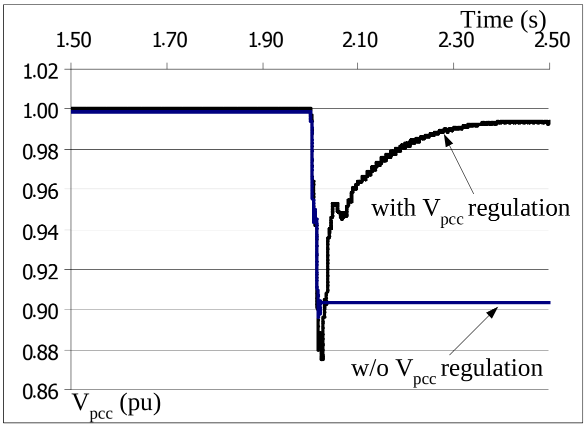

Fig. 9. PCC Voltage in Voltage Sag Compensation Mode

4. CONCLUSION

The control method for single phase PWM converter based on active and reactive current components has been proposed. The active current component is in phase with the supply voltage, while the reactive current component is in quadrature with the voltage.

The control loops for active and reactive currents have been derived and feed forward technique has been employed to decouple two current control loops.

The performances of the system were simulated and illustrated for three modes of operation. In the rectifying mode, the control objectives are to control the dc link voltage at the set value and the reactive current component is regulated according to the reactive power command. In the inverting mode, the active power is controlled to feed power to the ac system when the dc voltage increases to a level higher than the reference value. While in the voltage sag compensation mode, the PCC voltage can be restored back to the reference value, if the voltage drop occurs.

All three modes of the proposed method have been verified by simulations. The results reveal that a single phase PWM converter can effectively control with system operation based on active and reactive current components. With this scheme, both the active power and reactive power can be directly and independently controlled.

NOMENCLATURE

C	DC link capacitor
E	DC link voltage
i_{dc}, i_{Re}	DC current and renewable energy current
i_S, I_S	Supply instantaneous current and amplitude
m	proportional factor
P_{dc}	DC power
R_{dc}	DC equivalent resistance
R_S , L_S	Supply resistance and reactance
u_S, U_S	Supply instantaneous voltage and amplitude
V_{Spq}, I_{Spq}	Active and reactive voltage and current components
v_S, V_S	Fundamental component of converter terminal instantaneous voltage and amplitude
θ	Supply current phase angle
δ	Converter terminal voltage phase angle

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APPENDIX

In (12), the plant transfer function of dc link voltage can be represented as

$$\frac{E}{I_{Sp}} = \frac{1}{2}U_S \frac{1}{I_{\mathrm{Re}} + sCE}$$

The control block diagram for dc bus voltage controller is shown in Figure A1.

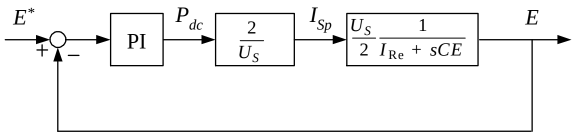

Fig. A1. Block Diagram of dc Voltage Loop Controller

In (10), the active voltage component (V_{Sp}) equation is the functions of I_{Sp} and dI_{Sp} $/dt$. The terms $-U_S - wL_S I_{Sq}$ in (10) can be treated as disturbances. Equation 10 can be rewritten as

$$-V'_{Sp} = R_S I_{Sp} + L_S \frac{dI_{Sp}}{dt}$$

Therefore, the control block diagram of current loop controller can be shown in Figure A2.

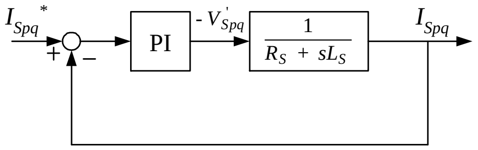

Fig. A2. Block Diagram of Active Current Loop Controller

The reactive current loop controller can be designed in the same manner as the active current loop controller.

Comparison of Fuzzy Logic Based and Conventional Power System Stabilizer for Damping of Power System Oscillations

K. Prasertwong, and N. Mithulananthan

Abstract— *This paper presents some interesting simulation results of a single machine infinite-bus system, with fuzzy logic based power system stabilizer (FLPSS). A comparison is also made between the FLPSS and conventional power system stabilizer (CPSS). In CPSS, one input signal, i.e. rotor speed deviation is used. However, in FLPSS, two input signals were used. The control input signals used in FLPSS are real power deviation and derivative of power deviation. It was found that FLPSS performs better than CPSS. However different operating points need to considered in both the cases to make a firm conclusion. Apart from its ability to give satisfactory operation at different operating conditions, it is possible to feed multi signal as control inputs in FLPSS. FLPSS design can be improved further, by considering fuzzification and defuzzification methods and changing other parameters.*

Keywords— **Fuzzy logic controller, Power System Oscillations, Power System stability, Power System Stabilizer.**

1. INTRODUCTION

Oscillations of small magnitude and low frequency often persisted for long periods of time and in some cases presented limitations on power transfer capability. Power system stabilizers were developed to aid in damping these oscillations via modulation of the generator excitation [1].

The basic function of a power system stabilizer is to extend stability limits by modulating generator excitation to provide damping to the oscillations of synchronous machine rotors relative to one another. These oscillations of concern typically occur in the frequency range of approximately 0.2 to 2.5 Hz, and insufficient damping of these oscillations may limit the ability to transmit power. To provide damping, the stabilizer must produce a component of electrical torque on the rotor which is in phase with speed variations [2], [3], [4], [5], [6].

Tuning of supplementary excitation controls for stabilizing system modes of oscillation has been the subject of much research during the past 20 to 25 years. Two basic tuning techniques have been successfully utilized with power system stabilizer applications: phase compensation and root locus. Phase compensation consists of adjusting the stabilizer to compensate for the phase lags through the generator, excitation system, and power system such that the stabilizer path provides torque changes which are in phase with speed changes. This is the most straightforward approach, easily understood and implemented in the field, and the most widely used. Synthesis by root locus involves shifting the eigenvalues associated with the power system modes of oscillation by adjusting the stabilizer pole and zero locations in the s-plane. This approach gives additional insight to performance by working directly with the closed-loop characteristics of the system, as opposed to the open-loop nature of the phase compensation technique, but is more complicated to apply, particularly in the field.

Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems. Basically, it provides an effective means of capturing the approximate, inexact nature of the real world [7]. Viewed in this perspective, the essential part of the fuzzy logic controller (FLC) is a set of linguistic control rules related by the dual concepts of fuzzy implication and the compositional rule of inference. In essence, then, the FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Experience shows that the FLC yields results superior to those by conventional control algorithms. In particular, the methodology of the FLC appears very useful when the processes are too complex for analysis by conventional quantitative techniques or when the available sources of information are interpreted qualitatively, inexactly, or uncertainly. Thus fuzzy logic control may be viewed as a step toward a rapprochement between conventional precise mathematical control and human-like decision making.

The fuzzy logic based PSS was proposed in [8] used two real-time measurements $\Delta\omega$ (generator speed deviation) and $\Delta\dot{\omega}$ (acceleration) as the input signal. In this paper, however, FLPSS uses active power deviation and its derivative as the input signals.

The power system stabilizer is a supplementary control system, which is often applied as part of the excitation control system [4]. The basic function of the PSS is to apply a signal to the excitation system; creating electrical torque's that damp out power oscillations. Since the primary function of the PSS is to add damping to the power oscillation, basic control theory would indicate that any signal in which the power oscillations are

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observable is a good candidate for input signal.

When consider the nature of the two input signals, speed and electrical power [4]. In general they both have some steady-state value, and may change slowly over long periods of time. For this reason, as is normally done in most PSS designs, a high pass filter is applied to both inputs. This filter is also called a washout filter, since it "washes out" or eliminates the low frequency signals. The form of the washout filter is as follows:

$$\frac{sT_w}{(1+sT_w)}$$

where T_w is the washout time constant, normally set in the range of 2 to 15 seconds. This gives a break frequency of $1/T_w$ rad/sec. If T_w is 10 seconds, then the filter breakpoint occurs 0.0159 Hz, well below intertie mode frequencies.

In reference [11], the author was discuss the experience in assigning PSS projects in an undergraduate control design course to provides students with a challenging design problem using root-locus, frequency-domain, and state-space methods. In this paper proposed an advanced techniques using fuzzy logic controller for damp power system oscillation. Thus parameter of conventional PSS is obtained in [11]. The MATLAB package, with the Fuzzy Logic Toolbox and Simulink, was used for the design [13].

2. POWER SYSTEM MODEL

A single-machine infinite-bus system in (Fig. 1) was used as the design model [11], usually used as the first step in designing an excitation system control for a power plant delivering an electric power [12]. The machine model includes sub-transient effects, and the field voltage actuator is a solid state rectifier. The machine delivers the electrical power P_e to the infinite bus. The voltage regulator controls the input u to a solid-state rectifier excitation, which provides the field voltage to maintain the generator terminal voltage V_{term} at a referenced value V_{ref}. The states for the machine are its rotor angle δ, its speed ω, and its direct- and quadrature-axis fluxes E'_q, ψ_d, E'_d, and ψ_q. The exciter is modeled with the voltage state V_R. All of the variables are normalized on a per-unit (p.u.) basis, except for δ which is in radians.

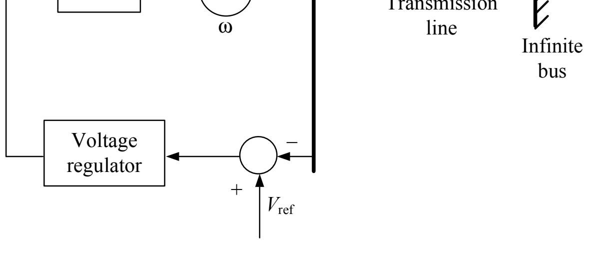

Fig.1. Single-machine infinite-bus system.

The power system model is linearized at a particular equilibrium point to obtain the linearized system model given in the state-space form

$$\Delta\dot{x} = A\Delta x + B\Delta u,\ \Delta y = C\Delta x \tag{1}$$

where Δ denotes the perturbation of the states, input, and outputs from their equilibrium values, with

$$x = \begin{bmatrix}\delta & \omega & E'_q & \psi_d & E'_d & \psi_q & V_R\end{bmatrix}^T \tag{2}$$

$$y = \begin{bmatrix}V_{term} & \omega & P_e\end{bmatrix}^T \tag{3}$$

The matrices for (1) derived from typical machine parameters are given in Appendix A. The dominant poles of (1) are the real poles s = -0.105 associated with the field voltage response, and the electromechanical (swing) mode s = -0.479 ± j9.33 with a small damping ratio ξ = 0.0513, representing the oscillation of machine against the infinite bus.

The input signal to a speed-input PSS is derived from the machine speed passed through a washout filter and several banks of torsional filters. The washout (derivative) filter $10s/(10s + 1)$ is a high-pass filter having a dc gain of 0, such that in steady state, the PSS path is not active. The aggregate phase lag effect of the torsional filters is represented by:

$$G_{tor}(s) = \frac{1}{1+0.061s+0.0017s^2} \tag{4}$$

The speed input stabilizer consists of a washout stage, a double lead/lag stage, and a filter to attenuate high frequency components [1].

Convention control design

Starting from (1), we were required to first use the terminal bus voltage signal V_{term} to design a high-gain voltage regulator (VR). Because the VR destabilized the swing mode, a PSS using the machine speed deviation signal was used to add damping to the swing mode. The feedback control system block diagram implemented in Simulink is shown in Fig.2.

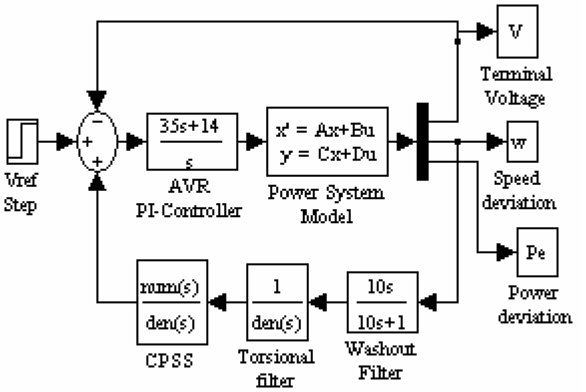

Fig.2. Simulink diagram of conventional power system stabilizer.

The process was specified in several tasks [11]:

(R1) For a 0.1-p.u. step in V_{ref}, simulate the V_{term} response of the open-loop system equation. (1) up to 10 s. Then with the PSS-loop open, repeat the simulation for equation (1) controlled by a proportional VR, $K_V(s) = K_p$ with $K_p = 10, 20, \ldots, 50$.

(R2) Make a root-locus plot of the voltage regulation loop using the proportional controller and find the gain K_u when the lightly damped swing mode becomes unstable.

(R3) Apply a PI controller for the VR

$$K_V(s) = K_{PI}(s) = K_P(1 + \frac{K_I}{s}) \qquad (5)$$

and plot the closed-loop V_{term} response to a 0.1-p.u. V_{ref} step input. Select the parameters from $0 < K_p < K_u$ and $0.1 < K_I < 10$ such that the rise time t_r is less than 0.5s and the overshoot M_p is about 10%. These specifications reflect the requirements of modern high-gain VRs. Detailed discussions of the rest design can be found in [11]. Fig.3 shows responses of terminal voltage to step in 0.1 pu V_{ref}, open loop and closed loop for K_p=10, 20,…50.

From [11], transfer function of CPSS is

$$\frac{num(s)}{den(s)} = \frac{221.48[s^2 + 5.88s + 8.6436]}{s^2 + 69.8s + 1218.01}.$$

Detailed discussions of PSS design technique based on the synchronizing and damping torque concept can be found in many references such as [1], [4]. In the PSS projects these ideas were translated into procedures that could be followed by students with basic control system design skills.

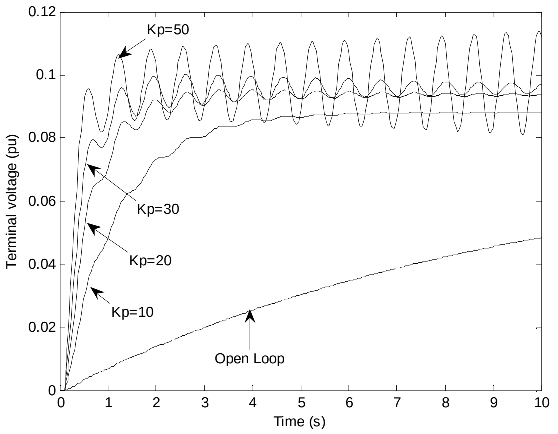

Fig.3. V_{term} responses to step in 0.1 pu V_{ref}, open loop and closed loop for K_p=10, 20,…50.

3. FUZZY LOGIC CONTROLLER (FLC)

Fuzzy logic controllers are rule-based controllers [10]. The structure of the FLC resembles that of a *knowledge-based* controller except that FLC utilizes the principles of fuzzy set theory in its data representation and its logic. The basic configuration of the FLC can be simply represented in four parts, as shown in Fig. 5.

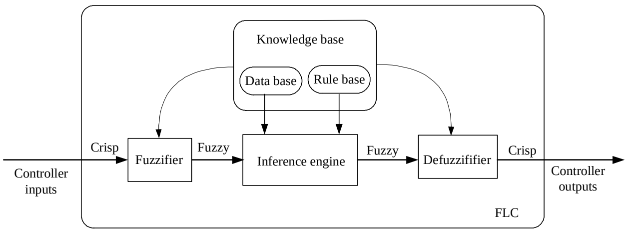

Fig. 5. Schematic diagram of the FLC building blocks

- *Fuzzification module*, the function of which are, first, to read, measure, and scale the control variable (e.g. speed, acceleration) and, second, to transform the measured numerical values to the corresponding linguistic (fuzzy) variables with appropriate membership values.
- *Knowledge base*, which includes the definitions of the fuzzy membership functions defined for each control variables and the necessary rules that specify the control goals using linguistic variables.
- *Inference mechanism*, which is the kernel of the FLC. It should be capable of simulating human decision making and influencing the control actions based on fuzzy logic.
- *Defuzzification module*, which converts the inferred decision from the linguistic variables back to numerical values.

Justification of Fuzzy Control Rules

There are two principal approaches to the derivation of fuzzy control rules [7]. The first is a heuristic method in which a collection of fuzzy control rules is formed by analying the behavior of a controlled process. The control rules are derived in such a way that the deviation from a desired state can be corrected and the control objective can be achieved. The derivation is purely heuristic in nature and relies on the qualitative knowledge of process behavior. The second approach is basically a deterministic method which can systematically determine the linguistic structure and/or parameters of the fuzzy control rules that satisfy the control objectives and constraints.

For example, Fig. 6 shows the system response of a process to be controlled, where the input variables of the FLC are the error (*E*) and error derivative (*DE*). The output is the change of the process input (*CI*). We assume that the term sets of input/output variables have the same cardinality, 3, with a common term {negative, zero, positive}. The prototype of fuzzy control rules is tabulated in Table 1 and a justification of fuzzy control rules is added in Table 2. The corresponding rule of region *i* can be formulated as rule R_i and has the effect of shortening the rise time. Rule R_{ii} for region *ii* decreases the overshoot of the system's response. More specifically:

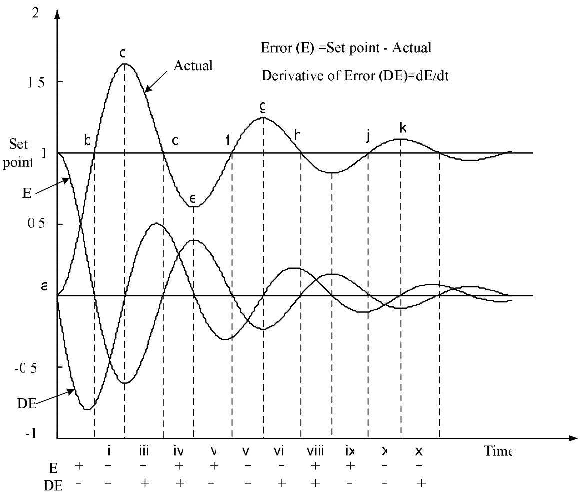

Fig.6. Rule justification by step response.

R_i: If (*E* is positive and *DE* is negative)
Then *CI* is positive,

R_{ii}: If (*E* is negative and *DE* is negative)
Then *CI* is negative.

Better control performance can be obtained by using finer fuzzy partitioned subspaces, for example, with the term set {NB: negative big, NM: negative medium, NS: negative small, ZE: zero, PS: positive small, PM: positive medium, PB: positive big}. The prototype and the justification of fuzzy control rules are also given in Table 3 and Table 4.

Table 1. Prototype of Fuzzy Control Rules with Term Sets {Negative, Zero, Positive}

Rule No.	*E*	*DE*	*CI*	Reference Point
1	*P*	*Z*	*P*	a, e, i
2	*Z*	*N*	*N*	b, f, j
3	*N*	*Z*	*N*	c, g, k
4	*Z*	*P*	*P*	d, h, l
5	*Z*	*Z*	*Z*	set point

Table 2. Rule Justification with Term Sets {Negative, Zero, Positive}

Rule No.	*E*	*DE*	*CI*	Reference Point
6	*P*	*N*	*P*	i (rise time), v
7	*N*	*N*	*N*	ii (overshoot), vi
8	*N*	*P*	*N*	iii, vii
9	*P*	*P*	*P*	iv, viii
10	*P*	*N*	*Z*	ix
11	*N*	*P*	*Z*	xi

Table 3. Prototype of Fuzzy Control Rules with Term Sets {*NB, NM, NS, ZE, PS, PM, PB*}

Rule No.	*E*	*DE*	*CI*	Reference Point
1	*PB*	*ZE*	*PB*	a
2	*PM*	*ZE*	*PM*	e
3	*PS*	*ZE*	*PS*	i
4	*ZE*	*NB*	*NB*	b
5	*ZE*	*NM*	*NM*	f
6	*ZE*	*NS*	*NS*	j
7	*NB*	*ZE*	*NB*	c
8	*NM*	*ZE*	*NM*	g
9	*NS*	*ZE*	*NS*	k
10	*ZE*	*PB*	*PB*	d
11	*ZE*	*PM*	*PM*	h
12	*ZE*	*PS*	*PS*	l
13	*ZE*	*ZE*	*ZE*	set point

Table 4. Rule Justification with Term Sets {*NB, NM, NS, ZE, PS, PM, PB*}

Rule No.	*E*	*DE*	*CI*	Reference Point
14	*PB*	*NS*	*PM*	i (rise time)
15	*PS*	*NB*	*NM*	i (overshoot)
16	*NB*	*PS*	*NM*	iii
17	*NS*	*PB*	*PM*	iii
18	*PS*	*NS*	*ZE*	ix
19	*NS*	*PS*	*ZE*	xi

Design two input signals of FLC

In this paper, crisp input values used in FLC are active power deviation and its derivative. The membership function and range of two input signals shown in Fig. 7 and Fig. 8.

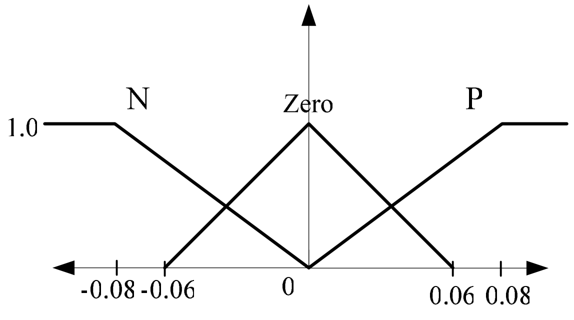

Fig.7. Three fuzzy sets of power deviation.

The membership function of stabilizing fuzzy set shows in Fig. 9.

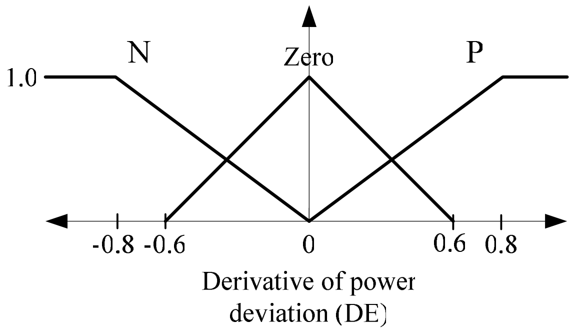

Fig.8. Three fuzzy sets of derivative of power deviation.

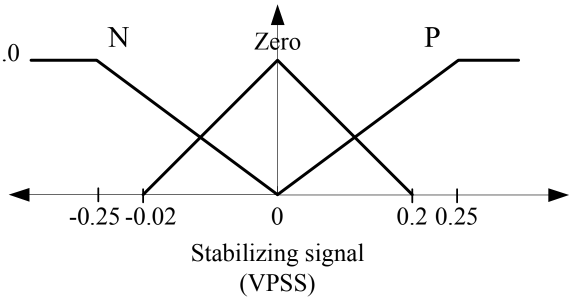

Fig.9. Three fuzzy sets of stabilizing signal (VPSS).

Table 5. Nine Fuzzy Control Rules for generate stabilizing signal

Derivative of power derivative (DE)

Power deviation (E)

	N	Z	P
N	N	N	N
Z	N	Z	P
P	P	P	P

The entries of matrix in Table 5 refer to the stabilizing signal as conditions of active power deviation and its derivative. Using Fuzzy Logic Toolbox [13] and Simulink drawing diagram show in Fig. 10. The parameters of FLPSS structure is choose fuzzy *mamdani* type, AndMethod using 'min', OrMethod using 'max', ImpMethod using 'min', AggMethod using 'max', and DefuzzMethod using 'centroid'.

4. SIMULATION RESULTS

Figure 11 shows a schematic diagram of the test system with CPSS and FLPSS. In order to trigger weak mode or oscillation, the system was perturbed with 0.1 p.u step change in reference voltage.

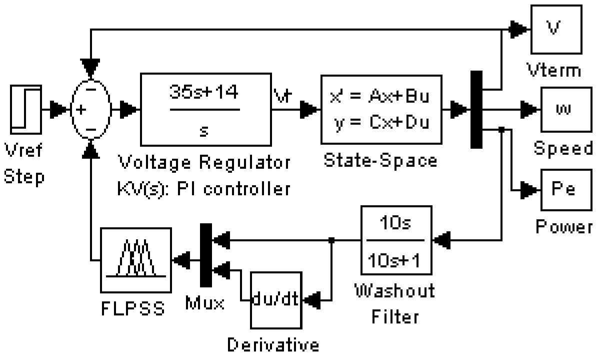

Fig.10. State space model of power system with FLPSS.

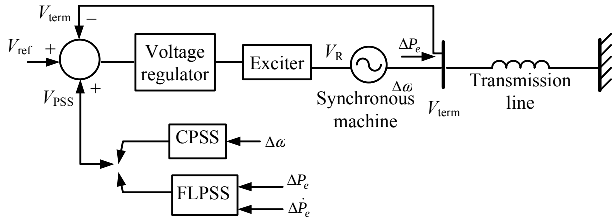

Fig.11. Single-machine infinite-bus system with CPSS and FLPSS.

Figure 12 shows power deviations of generator for all three cases, namely with PSS, with conventional PSS (CPSS) and Fuzzy Logic based PSS (FLPSS). As can be clearly seen from the response, the system without PSS is leading to oscillation with frequency around 1.5Hz and it takes more than 10 seconds for damping oscillation. With CPSS the oscillation triggered by step change is reference voltage is damped within 4 seconds. However, when FLPSS is introduced in the system, though the time taken for damping oscillation is the same the CPSS case, the amplitude of oscillation is lower. It should be noted that here FLPSS performance can be improved further by applying different membership function and also by considering better control input signals as FLPSS can accommodate many control input signals.

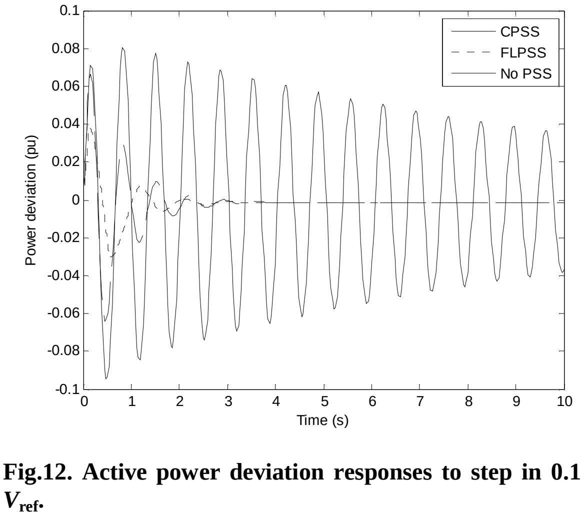

Fig.12. Active power deviation responses to step in 0.1 pu V_{ref}.

Similar pattern of responses can be observed in rotor speed deviation and excitation voltage as shown in Figs. 13 and 14, respectively.

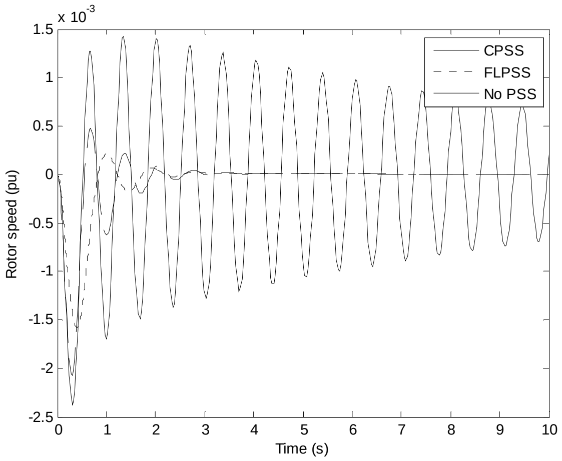

Fig. 13. Rotor speed deviation responses to step in 0.1 pu V_{ref}.

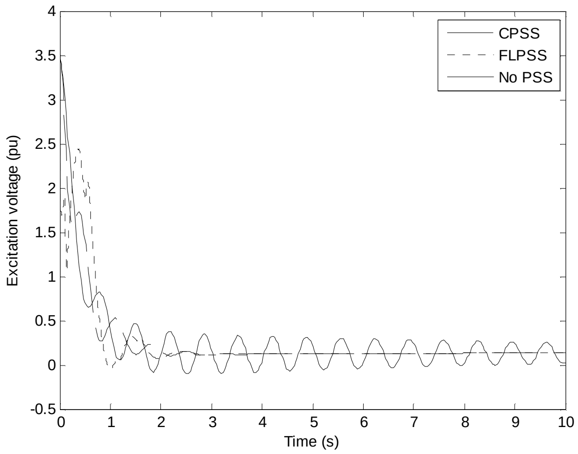

Fig.14. Excitation voltage responses to step in 0.1 pu V_{ref}.

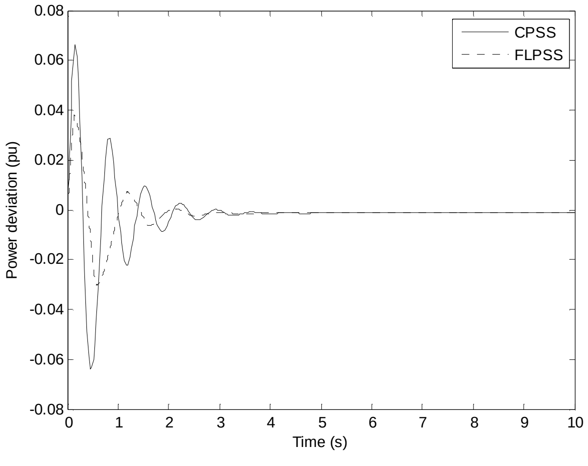

Fig.15. Active power deviation responses to step in 0.1 pu V_{ref}.

Figures 15 to 17 compare performances of CPSS and FLPSS. The time taken for damping and amplitude of oscillation are clear. As can be seen from figures the time taken for damping oscillation is slightly better in the case of FLPSS and the amplitude of oscillation is about 50% less than the case with CPSS. It should be noted here that power deviation and its derivative are used as control input signals.

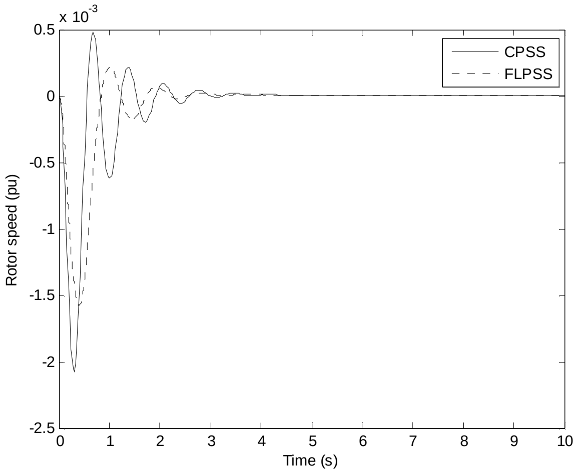

Fig.16. Rotor speed deviation responses to step in 0.1 pu V_{ref}.

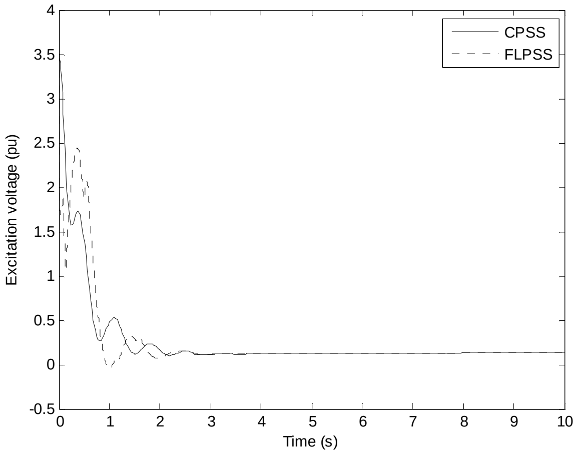

Fig.17. Excitation voltage responses to step in 0.1 pu V_{ref}.

5. CONCLUSION

The paper presents fuzzy logic-based PSS design for oscillation damping. It systematically explains the steps involved in fuzzy logic control design for oscillation damping in power system.

A comparison between the FLPSS and the CPSS shows that the FLPSS provides better performance than CPSS. The results show that the proposed FLPSS provides good damping and improves the dynamics.

Unlike the classical design approach which requires a deep understanding of the system, exact mathematical models, and precise numerical values, a basic feature of the fuzzy logic controller is that a process can be controlled without the knowledge of its underlying dynamics. The control strategy learned through experience can be expressed by set of rules that describe the behavior of the controller using linguistic terms. Proper control action can be inferred from this rule base that emulates the role of the human operator or a benchmark control action. Thus, fuzzy logic controllers are suitable for nonlinear, dynamic processes for which an exact mathematical model may not be available.

Using the principles of fuzzy logic control, a PSS has been designed to enhance the operation and stability of a power system. Results of simulation studies look promising.

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APPENDIX

APPENDIX A: STATE-SPACE MODEL.

Parameters of matrix A, B, C and D are used in the test system as following.

```
A=[   0      377.0     0        0        0         0        0;
    -0.246  -0.156  -0.137   -0.123  -0.0124   -0.0546    0 ;
    0.109    0.262   -2.17    2.30    -0.0171   -0.0753  1.27;
    -4.58     0       30.0    -34.3      0          0       0;
    -0.161    0        0        0      -8.44      6.33     0;
    -1.70     0        0        0      15.2      -21.5     0;
    -33.9   -23.1     6.86    -59.5    1.50       6.63    -114]

  B=[0;  0;  0;  0;  0;  0;  16.4]

  C=[-0.123  1.05     0.230   0.207  -0.105   -0.460    0;
        0      1        0       0       0        0      0;
      1.42    0.900   0.787   0.708   0.0713   0.314    0]

   D = [ 0; 0; 0]
```