Comparison of Singular and Modular Structures of Multiport Converters for Residential Applications in Smart Grids

Mohammad Jafari, Zahra Malekjamshidi, Md. Rabiul Islam, Jianguo Zhu, *Senior member, IEEE*

Faculty of Engineering and Information Technology, University of Technology Sydney
PO Box 123, Broadway, NSW 2007, Australia
Mohammad.Jafari@uts.edu.au

***Abstract*—This paper provides a systematic study on characteristics of a multiport converter with application in residential consumers of smart grid. The proposed converter can be used as a part of renewable energy system both in off-grid and grid connected customers. The study included several characteristics like efficiency, cost, reliability, flexibility and complexity of converters. Finally, the appropriate range of power and the modular structure are selected for the multiport converter. It is shown that a modular structure is preferable for residential consumers as it covers a wide range of demands. It also improves the reliability of renewable energy system especially in case of off-grid customers.**

***Keywords*—Multiport converter, modular, residential consumers, performance**

I. INTRODUCTION

There is an increasing demand on environmental friendly energy resources such as wind, solar and tidal [1]–[3]. Residential, commercial and industrial customers are able to contribute in supplying energy to the micro-grid using their personal renewable resources. Rooftop photovoltaic (PV) panels and low power wind turbines are being widely used to supply residential and commercial buildings in small and medium scales [4], [5]. According to the annual report of IEA/OECD, residential sectors consume almost 30 % of produced electricity [6]. Therefore, improvement in residential renewable energy systems can be a worthy and environmental friendly activity. Furthermore, installation of renewable energy systems in houses contributes the people in green energy programs and enables them to manage their electrical energy more efficient. Because of the intermittent nature of most of renewable energy resources such as wind, solar and ocean wave, combinations of two or more of these relevant power generation technologies, along with an energy storage system and/or alternative energy power generation can improve system performance [7], [8]. Multiport converters (MPC) play a very important role to integrate and interface the energy sources to supply the loads. Various MPC topologies have been proposed by researchers although there is not a general classification for these converters [9]–[12]. The MPC should be designed to work in both grid connected and off-grid applications. Fig. 1 shows the basic structure of hybrid renewable energy system using MPC. In general, there is not a big difference between grid connected and off-grid structures. In off-grid renewable energy system a stand by generator is used to improve the reliability of the system according to the absence of grid energy. While in grid connected mode it can be replaced by grid coupling point. The next difference is a dump load which usually will be used in off-grid operation in case of overcharge in battery. In most cases this dump load will be replaced by a house water heating system to prevent wasting electrical energy. The proposed MPC also is applicable to hybrid renewable energy systems of roadway lightings and traffic lights [13]. One of the other applications of MPC is in supplying the remote communication and broadcasting transceivers [14]. These remote stations usually are far from electrical grid and need a reliable and stable source of energy. The reminder of the paper is organized as follows. In Section II, a modular structure for MPC is suggested for application in residential consumers. A comparison between singular and modular converters is provided in Sect. III. Finally, the paper is concluded by brief remarks.

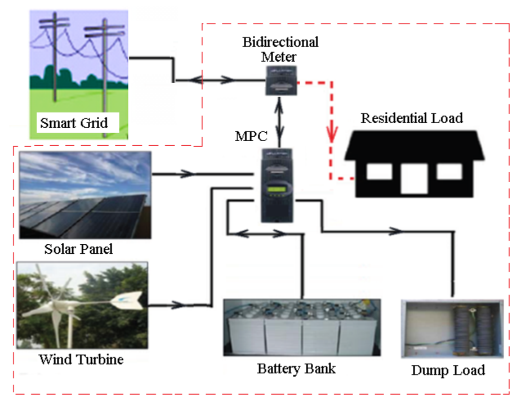

Fig. 1. Basic structure of hybrid renewable energy system including MPC.

II. DEFINITION OF SUITABLE RANGE OF POWER FOR MPC

To define an appropriate range of power for designed converter a primary study on relevant effective factors is required. As already mentioned, the main application of proposed MPC is in hybrid renewable energy systems. Residential consumers in urban areas mostly are interested to use only one renewable energy resource along with the grid energy. These groups of consumers rarely are interested in using hybrid renewable energies according to their grid accessibility. On the other hand in some cases the cost of grid energy can be less compared with installation of a hybrid energy system. Lastly, due to reliability of grid energy they are not interested in hybridization of renewable sources. Therefore, hybrid energy systems are more interesting for off-grid consumers because they are interested to produce their required energy as much as possible from the renewable resources and make it more reliable. This group of consumers can be categorized into the residential and non-residential consumers. The residential consumers mostly include farmers and poulterers which are living far from the grid network. The non-residential consumers of hybrid systems are mostly small scale commercial and industrial systems are using for research, communicating or monitoring services situated far from urban areas. Another application is in roads lighting as was discussed in the previous stages. The main point related to off-grid consumers is their wide range of demanded power changes from less than 1 kW up to 20 kW and even more. This feature prevents designers to design a unique system with a particular range of power for them. According to this problem, design of a modular system can be useful for this group of consumers. It can be applicable to a wide range of users with different range of power demands. A modular system also provides some features like more reliability and flexibility, better efficiency and power quality. It also provides better marketing, maintenance and service capabilities for manufacturing companies. For detail research on modular systems and to compare characteristics of modular and singular convertersa performance analysis between these two possible structures is provided in the next sections of paper.

III. Comparison of Modular Structures for Phase Shift Converter

The first step of this comparison is to define the possible structure of modular converter according to the application. Fig. 2 shows the proposed structure of modular system. As can be seen in this figure the structure of proposed MPC includes several parallel connected power modules and a single control unit as shown in Fig. 2. The power modules are the power boards including switching and drive components, high frequency transformer and filters. The same ports of modules are connected in parallel to each other via common input and output buses. The modules can be in active and de-active modes of operation according to the load demand, storage condition and sources energy. The active modules will receive the same control signals from the control unit as shown in the figure. The control unit provides control signals for paralleled modules according to their output parameters, condition of input sources and storage and load demand. It also receives some settings from operator and monitors some information. In the proposed structure, the control unit should be designed to be capable of controlling several paralleled power board with the same structure and it will be remained as constant part of MPC in all future expansions. The number of paralleled boards can be extended according the customer demand. To compare modular and singular structures, several

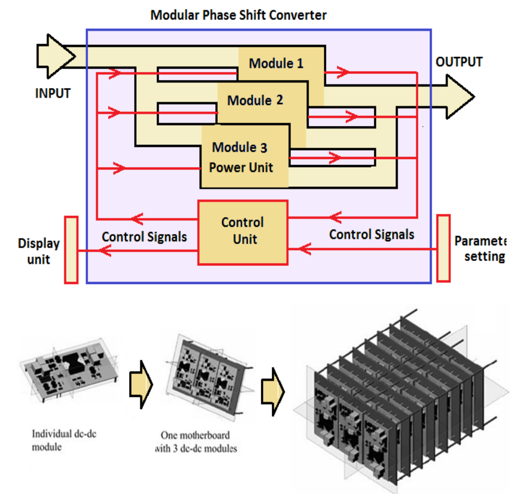

Fig. 2. Structure of proposed modular MPC.

parameters are selected as indicators. The main selected parameters selected for comparison are efficiency, cost, reliability, flexibility, and control complexity. The comparison procedure is based on previous author's publication [15].

A. Efficiency

One of the important factors in evaluation of converter quality is the efficiency. Customers are always interested in using systems with the higher efficiencies. This factor is more important in hybrid renewable energy systems especially in off-grid customers as input energy for this group of consumers is limited and intermittent. One of the drawbacks in efficiency of power electronic systems is that their efficiency normally decreases both in light and full load conditions and they provide the highest efficiency in their medium load conditions [16]. On the other hand normal load profile of residential consumers shows that these consumers most of the times (70–80 % of daily hours) are operating in light or full load conditions. The modular structure can improve the converter efficiency both in light and full loads conditions [17], [18]. This improvement is based on management of number of active and de-active modules according to the load conditions. The system can be designed that all active modules operate at medium load with the highest possible efficiency when the overall load in considerably high. On the other hand in light load conditions the number of active modules can be reduced by control unit which causes a moderate load and high efficiency operation for remains of active modules. Fig. 3 shows the efficiency improvement for double and triple module converters compared with single module converter. The efficiency of converter improved considerably both in light and full load conditions in case of using two and three paralleled module compared with a single module. The next positive point of using modular system to improve the efficiency of converter is that the low power systems are able to operate in higher switching frequencies and employing soft switching techniques is possible in this range of power and frequency. Using zero voltage switching (ZVS) and zero current switching (ZCS) in low power, high frequency modular boards improve the efficiency of each module and consequently overall modular system. This is because the efficiency of a modular system combined of N similar

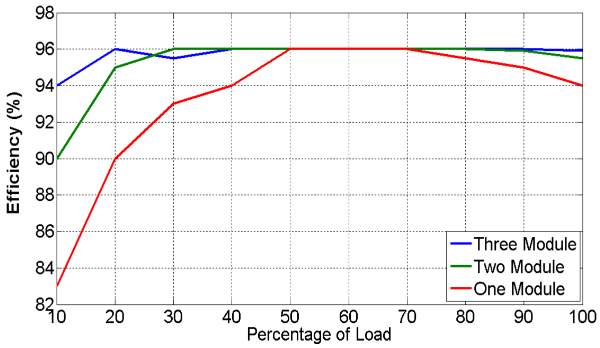

Fig. 3. Comparison of efficiencies for single, double and triple module converters.

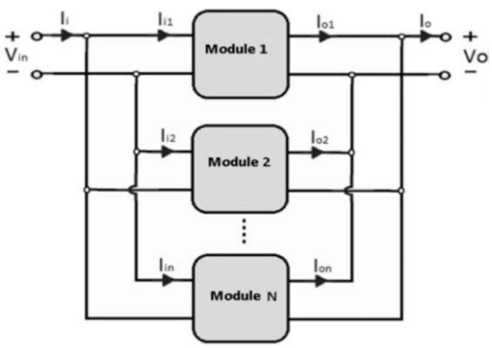

Fig. 4. Structure of modular MPC including N similar paralleled converter.

paralleled module, as shown in Fig. 4 is equal to the efficiency of each single module. This means that any improvement in single modules can be resulted in improvement of overall modular system efficiency. This theory is proved for the system shown in Fig. 4. The efficiency of J-th module of converter can be calculated from

$$\eta_j = \frac{V_o I_{oj}}{V_i I_{ij}}, j = 1,2,\ldots,N \tag{1}$$

And the output current in J-th module can be calculated from

$$I_{oj} = \frac{\eta_j V_i I_{ij}}{V_o} \tag{2}$$

The output current and input current in modular converter can be calculated form (3) and (4).

$$I_o = \sum_{j=1}^{n} I_{oj} \tag{3}$$

$$I_i = \sum_{j=1}^{n} I_{ij} \tag{4}$$

Using (2), (3) and (4) the converter efficiency can be calculated from

$$\eta_T = \frac{V_o I_o}{V_{in} I_i} = \eta_j \tag{5}$$

As a result, it was shown that the efficiency of modular converter is dependent to the efficiency of each module and in case of using similar modules the efficiency of converter is equal to the efficiency of its modules.

B. Reliability

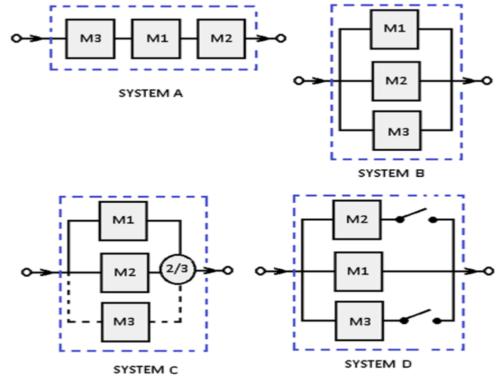

Fig. 5. Various structures of modular systems.

Reliability is of the important factors withholding the use of power electronic systems in some applications. There are different methods for design and development of power electronic converters to increase their reliability [19]–[21]. In general the reliability assessment of converter depends on reliability of each main block of converter and the reliability of each block depends on failure rate of its included components. The reliability of a single module converter is a function of failure rate and can be calculated from

$$R(t) = e^{-\lambda_s t} \tag{6}$$

The equation (6) shows that the converter reliability is an exponential function with a time constant defined by failur rate. It shows that the reliability of systems with higher failure rate will decrase faster with the operating time. The failure rate for a modular system depends on the series or parallel connections between the converter modules. The reliability of a modular system with several blocks such as what is shown in Fig. 5 can be defined according to equations (7) to (10) for systems A, B, C and D, respectively. The system A is a series connected modular system. The reliability of such a system is equal to the multiplication of all modules as is shown in (7).

$$R(t) = R_1(t).R_2(t)\ldots R_n(t) = \prod_{i=1}^{n} R_i(t) \tag{7}$$

In system B, the modules are connected in paralel form and the reliability function for such a systm with (n) paralleled module can bedefined using (8).

$$R(t) = 1 - F_1(t).F_2(t)\ldots F_n(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)) \tag{8}$$

The system shown as C in the figure is called a *(K out of n)* system or an active (on-line) redundancy system. As is clear in the figure, the actual number of modules required to cover the demand is two and the third module always is in parallel connection to increase the reliability of system. The reliability of this system including (n) paralleled module that K of them are paralleled as redundant modules can be calculated according to (9).

$$R(t) = e^{-\lambda_s t}\left[1 + \lambda_s t + \frac{(\lambda_s t)^2}{2!} + \ldots + \frac{(\lambda_s t)^{n-1}}{(n-1)!}\right] \tag{9}$$

The last type of modular systems shown as D is known as passive (off-line) redundancy. In this type of systems, the reliability factor for a *n*-unit system can be calculated as below. In this equation, we assume that all modules are the same with the same failur rate of λ_s.

$$R(t)=\sum_{r=k}^{n}\binom{n}{k}R(t)^{r}(1-R(t))^{n-r} \tag{10}$$

The proposed modular MPC in case of reliability assesment can be same as system (D). According to this equatoion as the number of modules increases the reliability will increase. In Fig. 6, the reliability of single, double and triple module converters is compared for a failure rate of 7 per milion hours of operation. It can be seen that the reliability in triple module system improved considerably compared with single module converter. Also as the number of modules increases the rate of improvement in reliability decreases. Therefor, according to the maintanance and cost issues of additional standby modules a decision on increasing their number should be made carefully. Based above discussion on reliability it seems that reliability of modular systems is higher than centralized structure DC converters. The modular converter provide better reliability for consumers especially off-grid ones who need more reliable renewable energy systems.

C. Flexibility

In this section, it is shown that the modular systems are more flexible compared with single units in operation, production and marketing. As is shown in Table I, for a 20 kW modular unit if 1 kW modules is used the converter has 20 modes of operation or 20 states of activating paralleled modules. As the rated power of modules increase the number of possible operation states will decrease. For example, a 20 kW converter can be made by 4 modules of 5 kW which means it can only operates in states of one, two, three and four paralleled modules which provide the power ranges (0–5 kW), (0–10 kW), (0–15 kW) and (0–20 kW), respectively.

The next positive point of modular systems is their flexibility in production, marketing, service and maintanance and future extension. Modular systems provide the same power unit with the same charateristics and components for a wide range of consumers with different power ranges. Therfore, with the same unit a higher range of products and customer options can be provided. On the other hand manufacturing, service and maintanance of same units is more convenient and any future extension of renewable energy system can be done by increasing the number of paralleled power units.

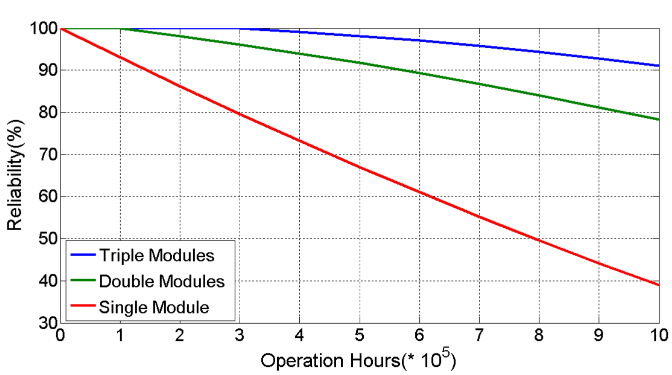

Fig. 6. Comparison of reliability in single, double and triple module converters.

Fig. 7 shows that for modules produced in higher range of rated power the flexibilty of production will decreas. For example for a power range of (0–20 kW) if 5 kW modules are produced the number of products are four type (5, 10, 15 and 20 kW) while for a 2.5 kW module this will increse to eight type. The main point is that although the lower power modules will increase the flixibilty but they will increase the overall cost of converter especially in higher ranges of power. It can be concluded that modularity can increase flexibility of the converter in production, marketing, service and maintenance and provides a various modes of operation for MPC.

D. Complexity

Although modularity has many advantages against the centralized systems it also can increase the complexity of entire system. According to the structure of the proposed modular system shown in Fig. 2, it can be seen that the control board is a common unit to control all paralleled power modules. As the power modules are similar they generally need same control signal. Based on this idea, increasing the number of paralleled modules only increases some protection and communicating signals. These signals do not have any considerable effect on complexity of the overall modular MPC. The result is that modularity does not increase the complexity of the system considerably.

E. Cost

One of the important factors in evaluation of modular systems is their extra cost compared with the centralized units. Generally the overall cost of converter will increase as the number of parallel connected modules increase. The main point is to find the percentage of additional cost that modularity implies on overall converter cost compared with centralized system. In the following sections, the effect of modularity on overall cost of converter is discussed. It is shown that the most appropriate range of power of modules for a modular converter according to its application in off-grid consumers is 5 kW.

TABLE I.
NUMBER OF OPERATING STATES FOR 20, 15 AND 10 KW CONVERTERS

	$1kW$	$2kW$	$3kW$	$4kW$	$5kW$	$6kW$
$10kW$	10	5	4	3	2	2
$15kW$	15	8	5	4	3	3
$20kW$	20	10	7	5	4	3

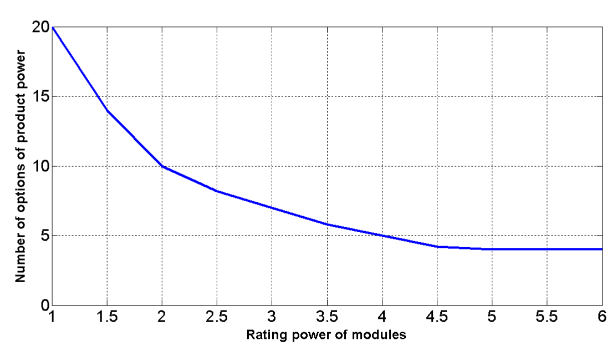

Fig. 7. The number of possible products of each module systems versus power rating of module.

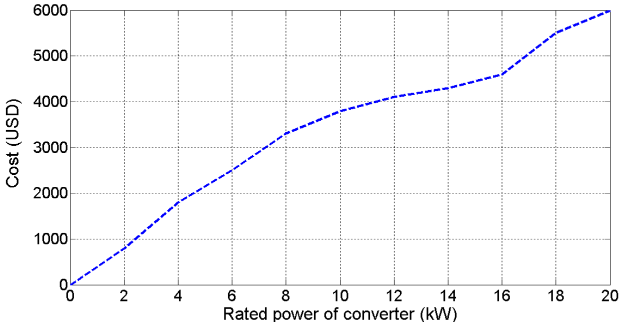

Fig. 8. Cost of converter based on average price of its main components.

Fig. 9 shows the average of converter cost according to the rated power. The graph was drawn based on cost of main components in converter blocks [12]. To calculate the average price of a converter based on the main components, the first step is calculating the cost of each block in converter based on the average price of components by

$$\alpha_i = \sum_{k=1}^{n} \delta_k . \lambda_k \tag{11}$$

In this equation λ_k is the cost of *K*th main component and δ_k is the quantity of component in the block. The main components are diodes, switching devices, capacitors, inductors and high frequency transformer and the main blocks are input filter, output filter, dc to ac conversion and ac to dc converter. The next step is calculating the converter cost which can be achieved by addition of costs of blocks as shown in (12).

$$C_j = \sum_{i=1}^{n} \alpha_i \tag{12}$$

As is illustrated in the figure the converter cost goes up as its rated power increase. The reason is that the higher power means the components with higher ratings which results in a higher cost. The graph in Fig. 8 is used as a reference for comparison of overall cost in modular systems based on modules rated power. According to this information the percentage of additional cost of modular systems compared with singular systems for power ranges of 10, 15 and 20 kW is calculated and shown in Fig. 9. The percentage of additional cost is defined as

$$K_A(\%) = \frac{100(C_M - C_S)}{C_S} \tag{13}$$

where C_M is cost of modular system and C_S is cost of singular system. As can be seen in this figure the percentage of additional cost of modular systems goes up with increasing power range. The average percentage of additional cost for a 20 kW system is about 50 % while this decreases to 35% and 25 % for 15 kW and 10 kW systems respectively.

The next point is that the average of additional cost for all three type modules minimized when the rated power of each module is selected in ranges (2–2.5 kW) and (5–5.5 kW). The first minimum point is because lower cost of low power modules because of using low power components. The second minimum point is because of reduction of number of paralleled modules for systems with higher power range. The highest average is in case using low power modules (1–1.5

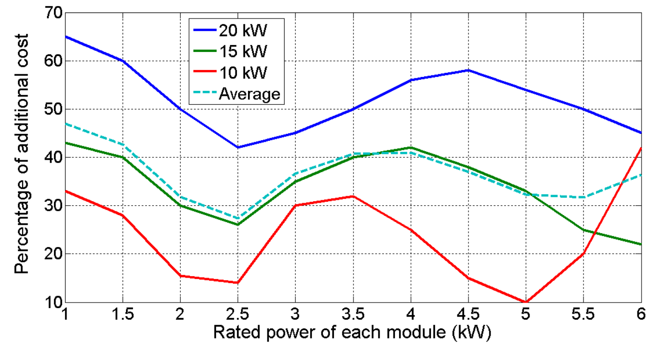

Fig. 9. Average percentage of additional cost for modular structure compared with centralized structure for various power ranges of dc converter systems.

kW) because of increasing the number of modules. In case of using modules with power range 5.5–6 kW the average cost increased because additional cost in 10 kW systems. According to the information showed in Fig. 9 the best range of power for each module in a modular converter can be in ranges (2–2.5 kW) or (5–5.5 kW) where the average of additional cost minimizes. We select the range of 5 kW as an appropriate range of power for modules in our proposed phase shift converter.

Selection of the next minimum point (2–2.5 kW) increases the number of modules especially in higher ranges of power and causes a higher size of converter. The next point that can be seen in this figure is that the average of percentage of additional cost for these three ranges of modular converters is fluctuating between 30 to 40 % for all range. On the other hand, according to a survey from several companies it can be seen that the cost of converter in average is 23 % of overall cost of hybrid renewable energy system including wind turbine, solar panel, battery and converter. Based on this the percentage of average of additional cost of using modular system compared with a singular system changes between 6 to 10 % of overall cost of hybrid renewable energy system. According to what is discussed in this section, the additional cost that a customer with power consumption of 5–20 kW should pay for the modular system is less than 10 % of overall renewable energy system. According to advantageous of modular converter compared with centralized one it seems that most of off-grid consumers will be happy to pay this additional cost.

IV. Selection of Modular Structure

To compare the characteristics of modular and centralized converter, firstly their characteristics should be normalized. In general there are two methods of normalization. The first method is used to normalize the parameter between zero to one; can be calculated from [22], [23]

$$X_i(norm) = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{14}$$

$$0 \le X_i(norm) \le 1$$

Under second method the normalized parameter can be calculated from

$$X_i(norm) = \frac{X}{X_{\max}} \quad , \frac{X_{\min}}{X_{\max}} \leq X_i(norm) \leq 1 \tag{15}$$

At the next step the normalized parameters will be added to each other using some weighting factors. The weighting factors are adjusted according to the importance of that parameter in evaluation their value should be in range 0–100 and their summation should be equal to 100 as shown below.

$$\sum_{i=1}^{n} \delta_i = 100 \tag{16}$$

Using weighting factor and normalized value of each parameter and adding them for both modular and centralized structure will results the evaluation factor. It ranges between 0–100 and is calculated from

$$Evaluation \quad factor = \sum_{i=1}^{n} [\delta_i . X_i(norm)] \tag{17}$$

The result of comparison between centralized and modular structure and the weightnig factors are shown in Table II. The results shown that the modular system has a higher evaluation factor of 92 against the 62.5 for centralized structure and it can be selected as favorite structure for proposed phase shift converter.

TABLE II.
EVALUATION RESULTS OF MODULAR AND CENTRALIZED SYSTEMS

	Modular System	*Centralized System*	*Weighting Factors*
Efficiency	1	0.85	25
Re*liability*	1	0.25	30
Flexibility	1	0	10
Cost	0.75	1	25
Complexity	0.65	1	5
Other Performances	1	0.75	5
R*esult*	92	62.5	100

IV. CONCLUSION

It can be concluded that a modular structure with the rating power of 5 kW for each module can be a good choice for the multi-port converter with application in residential consumers. The proposed converter provides satisfactory characteristics in case of flixibility, reliability and efficiency in both islanded and grid connected mode of operations. It was shown that this structure casues an additional cost of 20–30 % on converter cost and 6–10 % on all renewable energy system which is not considerable looking at its advantages.

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