BALKAN JOURNAL OF ELECTRICAL & COMPUTER ENGINEERING, Vol. 9, No. 2, April 2021

The Topologies of Multi-Input Single-Output Non-Isolated DC-DC Converter for Distributed Power Generation

Cihat Şeker, M. Tahir Güneşer and Şakir Kuzey

Abstract—**Today it is an obvious fact that energy consumption tends to increase due to technological developments, population growth, and increasing living standards. In last two decades, renewable energy sources are considered to be the most convenient way to produce clean energy, as it has infinite energy potential. However, most of these alternative systems are not considered sufficient to supply the whole demand alone. But hybrid systems with some alternative energy sources, such as solar, wind, and biomass appear to be a solution to supply the energy needs in the future. In hybrid systems, the DC-DC converter structure is the main device when converting energy for the proper loads. Single/multiple inputs, single/multiple output DC-DC converter topologies vary in design according to the energy demand of the load. Particularly, as the power flow direction differs depending on the energy need and efficiency in energy systems, the usage areas of topologies with bidirectional power flow and fewer circuit elements that reduce system cost and complexity are expanding. In this study, the simulation of multi-input single-output (MISO) DC-DC converter topologies were performed in Matlab / Simulink software. Inductor current and voltage, output current and voltage, as well as output power used in the determining topologies were analyzed. The mathematical equations given in the topologies were confirmed by simulation studies.**

Index Terms—**MIC topologies, hybrid systems, Matlab / Simulink, two-input converters, V-I characteristics**

I. Introduction

IN THE process from generation to the consumption of electrical energy, the most important reason for using alternating current (AC) is that the input voltage can be easily converted to different voltage levels with the help of low frequency transformers (LFT). In electrical power systems, LFTs also perform electrical insulation functions besides voltage transformations. However, LFTs constitute the biggest part of the power systems in terms of volume, weight and cost due to the weight of the bulky iron core and copper coils in their structure. The dimensions and weights of transformers vary depending on the ferromagnetic properties of the cores used in their structures and the temperature of the cores and windings.

In power transformers, while the temperature of the transformer is controlled with the help of various cooling devices placed on the transformer, a reduction in weight and volume can be achieved by using materials with high magnetic permeability in the core structure. On the other hand, since the transformer sizes change inversely with frequency, increasing the frequency can reduce the transformer dimensions. However, since increasing the frequency will increase the losses caused by hysteresis and eddy current, there is a need for cores with high magnetic permeability instead of conventional magnetic cores. With advances in material science, cores with high power and high magnetic permeability can be developed at medium voltage levels [1-3].

Today, using the only transformer is insufficient in meeting the needs of loads with different profiles and in connect of renewable energy sources such as solar and wind to the grid. Additional mechanisms are needed to overcome power quality problems such as voltage rise and fall, ripple, or harmonics [4]. With the advances in semiconductor technology, power electronics has emerged as a promising solution to dealing with the problems of complex power systems. High-power and controllable solid-state switches triggered the development of various power electronic converters that find application in both transmission and distribution systems. Power electronic circuits and mechanisms (such as fuses, switches, protection equipment, etc.), initially created with the help of transistors, were primarily used in the industry. This process, which started with motor control units, went beyond the industry thanks to the developing semiconductor technologies and went to electric vehicles [5,6], microgrids [7,8], renewable energy sources [9,10], home, office, agriculture, and animal husbandry [11, 12] has found use in many places. Power electronic circuits, whose production and consumption increased with the increasing demand, made it necessary to

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Manuscript received January 6, 2021; accepted February 17, 2021.
DOI: 10.17694/bajece.855262

minimize the effect of load effect on the source and peripheral devices and to be compatible with each other. Besides, the quality and uninterrupted energy demands of the users [13] made it necessary to provide power quality, efficiency, safety, and insulation features. It is necessary to prevent wide-ranging power outages that occur in case of malfunctions, to dampen disturbing effects, and to keep the power factor level that creates a load on the grid at the optimum level.

Power converters that result from the combination of conventional transformers and semiconductor converters are defined as power electronics transformers (PET). PET's were first patented by Murray in 1970 [14]. Using conventional transformers in PETs provides easy conversion between different voltage levels as well as electrical insulation. However, transformers used in the network frequency (50Hz / 60Hz) have disadvantages such as very large weight and dimensions depending on the power. Brooks suggested in 1980 that by increasing the frequency of the insulation barrier, the size of the system could be reduced and more power could be transferred with a smaller transformer [15]. Thus, together with transformers that can be operated within the frequency application limits, the way for very high energy conversions from very small dimensions has been opened. It has started to widespread the use of PET instead of LFT, especially at low and medium voltage levels. Safe and efficient power control is provided in a wide range by properly controlling the power electronic elements in the PET's structure. Compared to conventional transformers, PETs are characterized by high power density, small volume, and weight, controlled power factor, controlled voltage reduction, etc. It appears to have good features such as [16,17]. On the other hand, as a result of increasing the operating frequency, the size of the filter elements is reduced, allowing high energy conversions from low volumes [18]. In the light of advances in materials science, PETs have developed in parallel with semiconductor circuit elements.

In this study, the studies on multi-input converters (MICs) are examined and MIC topologies, which are widely included in the literature, are summarized. MIC topologies are grouped under four subtitles as AC / AC, AC / DC, DC / AC, and DC / DC. Topology structures are generally examined and detailed with a sample application. The developed MIC was simulated in Matlab / Simulink environment. The findings obtained from the design criteria and simulation are presented in the third section of the study.

II. MULTI-INPUT DC/DC SYSTEM

A simulation study of the MISO DC-DC converter system given in [19, 20] has been done. In such multi-input (MI) systems, a separate DC-DC converter is used for each source. The output of the transformers of the sources was connected in series and a single DC output voltage was generated. In such systems feeding a single load, using a separate converter for each source stands out as a disadvantage. According to the given topology, a two-input single-output circuit model was formed in the simulation environment in Matlab / Simulink program. The circuit model is given in Fig. 1. Aleo Solar S16.185 PV module in Matlab / Simulink software library was used.

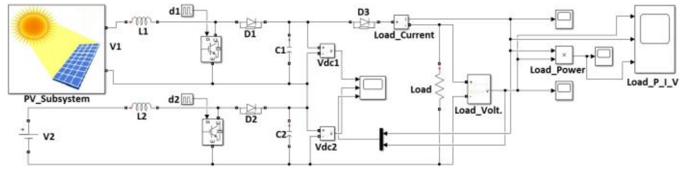

Fig. 1. Two-input single output DC-DC system

The use of boost converters separately for two DC sources is given in Fig. 1. V_1, V_2 the source is chosen as *24* V_{DC}. There is a unidirectional flow of power from the sources to the load. The load voltage (V_0) can be found by equation 1.

$$V_0 = V_{DC_1} + V_{DC_2} = \frac{V_1}{1-d_1} + \frac{V_2}{1-d_2} \tag{1}$$

Equation 1 is determined according to the two-input DC-DC system. Depending on the number of entries, the equation can be expanded. V_{DC_1}, V_{DC_2} are the output voltage of the boost converters, d_1 and d_2 are the duty cycle values of the first and second switches, respectively. If the input values ($V_p = V_1 = V_2$) and duty cycle ($d_p = d_1 = d_2$) values for each switch are equal, the output voltage V_0 can be generalized with equation 2 according to the number of sources (n).

$$V_0 = \frac{nV_p}{1-d_p} \tag{2}$$

Capacitance value (C) is found by Equation 3.

$$C = \frac{n^2 d_p}{1-d_p} \frac{V_p}{R \cdot f \cdot \Delta_{V_p}} \tag{3}$$

where R is load, f is the switching frequency, and Δ_{V_p} is the fluctuation in voltage. Switching frequencies in topology are fixed. Inductor value (L) is given by Equation 4.

$$L = \frac{(1-d_p)^2 d_p \cdot R}{2 \cdot n \cdot f} \tag{4}$$

The parameters and values used in the simulation environment are given in Table I. For a two-input system, the duty cycle ratio is taken as 0.4 in both switches. Input voltage source values are equal and voltage ripple value is taken as $2\ V$.

TABLE I
CIRCUIT PARAMETERS

Parameter	Value
V_1 (mpp)	24 V_{DC}
V_2	24 V_{DC}
d_1	40 %
d_2	40 %
L	18 μH
C	160 μF
R	10 Ω
f	20 kHz
Δ_{V_p}	2 V

Fig. 2 shows the output DC voltage and current graph for the load in each converter. The output voltage is measured at *48.5V*. The output current has been measured as *4.95A*.

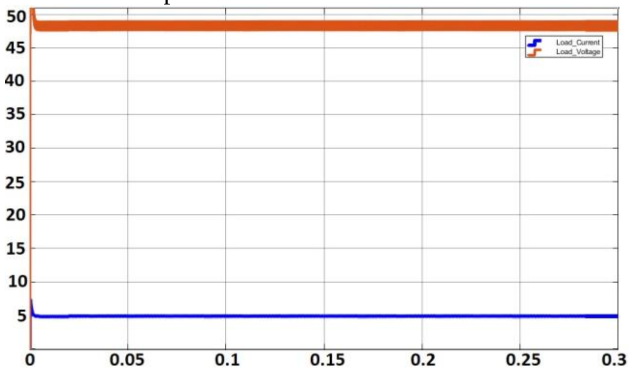

Fig. 2. I_0 and V_0 graph

The output power graph is given in Fig. 3 and it has been calculated as approximately *240 W*.

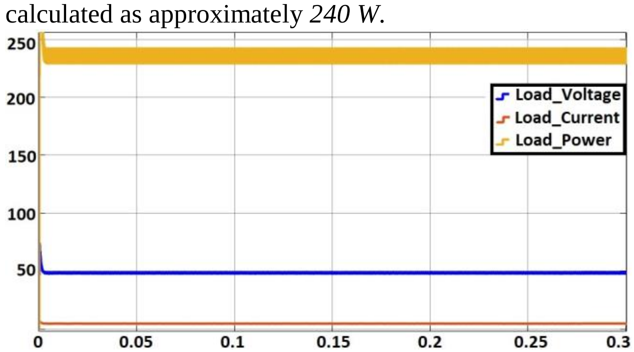

Fig. 3. P_0,V_0 and I_0 graph

III. MISO DC/DC CONVERTER TOPOLOGIES

There are many MI DC-DC converter topologies in the literature. In such systems, power transfer with a common circuit using more than one source and a single inductor was performed either in unidirectional or bidirectional. Meeting the energy needs increases its importance day by day. In this case, the hybrid use of renewable energy sources of different voltage levels is seen as a solution. For this reason, the use of two different voltage levels was preferred in the study, and the number of voltage sources with different profiles can be increased according to the energy need.

MISO DC-DC converter topology is given in [21, 22]. The pulsating voltage source cell (PVSC) structure formed by the parallel connection of diodes to the sources forms the basis of the system. In the topology, the power flow is provided unidirectional with a converter with a single output filter and a single control system. The circuit model is given in Fig. 4. V_1 and V_2 DC power supplies can supply power to the load both separately and simultaneously. By applying PWM signal switching, four different operating modes are formed at the fixed switching frequency. Mode 1; It is the time interval when the switch S_1 is on and the switch S_2 is in an off position. In this time interval, the energy from the V_1 source feeds the load through the inductor. Mode 2; It is the time interval when the switch S_1 is off and the switch S_2 is on. During this time, the V_2 source charges the inductor. The output capacitor supplies power to the load. Mode 3; It is the interval when both switches are off. In this time interval, it provides its load power from the energy stored in the inductor and the capacitor. Mode 4; It is the time interval when both switches are on. During this time, both sources work at the same time. The sources charge the inductor and the power of the load is provided by the capacitor. Since it has four different operating modes, the PWM signal applied to the switches must be applied in a way that creates these modes. Switches are operated at the same frequency. The output voltage V_0 of the system can be found by Equation 5.

$$V_0 = \frac{d_1V_1 + d_2V_2}{1-d_2} \tag{5}$$

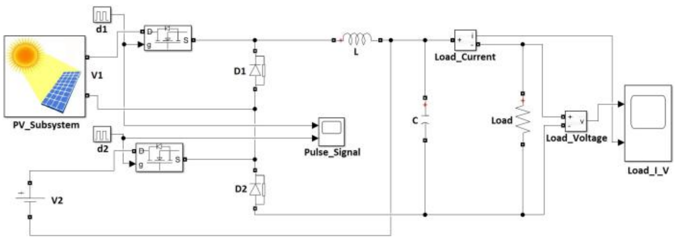

Fig. 4. Two-input single-output buck / buck-boost converter circuit

If the source with high voltage value is defined as V_H and the source with low voltage value as V_L there is a relationship between input voltages and output voltage as $V_H > V_0 > V_L$. The parameters used in the simulation environment are given in Table II.

TABLE II
CIRCUIT PARAMETERS

Parameter	Value
V_1 *(mpp)*	24 V_{DC}
V_2	12 V_{DC}
d_1	40 %
d_2	28 %
L	82 μH
C	160 μF
R	10 Ω
f	20 kHz

The signals used in the simulation study of two input DC-DC converter topologies are given in Fig. 5.

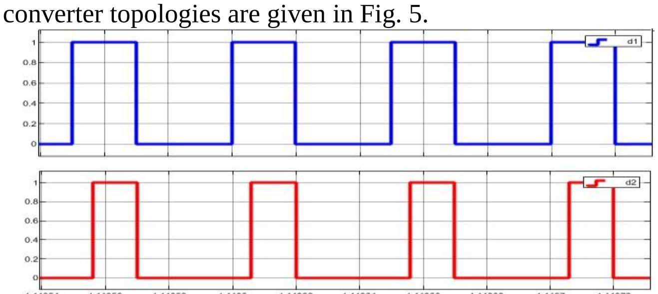

Fig. 5. d_1 and d_2 duty cycle graph

When the power control relationship of the circuit is examined, it is seen that three different situations occur. The V_1 or V_2 source will be the main source that provides the power needed by the load, and the remaining power will be

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supplied from another source. The third case is that both sources will provide power to the load and always provide the highest power to the output by controlling the input currents. Fig. 6 shows the output current and output voltage graph.

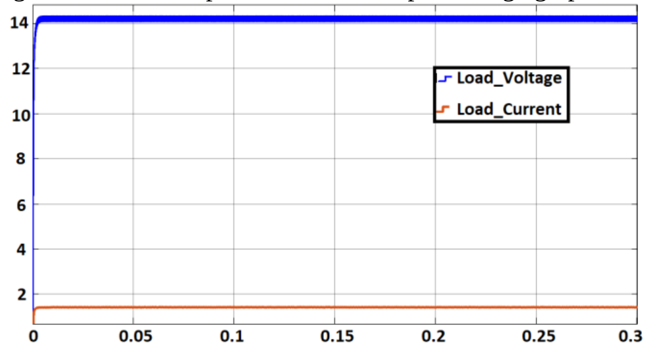

Fig. 6. V_0 vs I_0 graph

The circuit structure with a common converter structure utilizing a single inductor that provides bidirectional power flow analysis is given in Fig. 7. Contrary to the topologies given in the previous sections, it provides bidirectional power flow. This is particularly desirable for electric vehicle applications. For example, the power to be generated during regenerative braking in electric vehicles (EVs) is desired to be recovered. This situation points out that there should be a converter that can provide bidirectional power in EV systems. In the literature, many studies have been done for different modes of this topology [23-27].

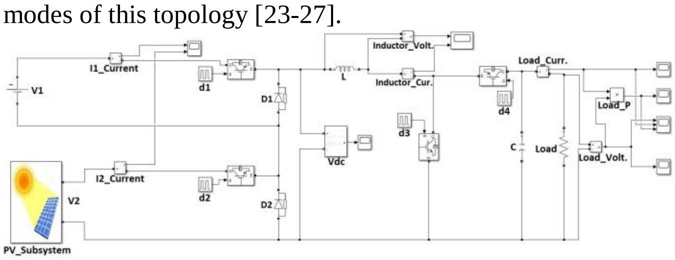

Fig. 7. MISO DC-DC converter topology

S_1 and S_2 switches determine which source will provide power, S_3 switch to determine whether the converter will operate in buck, boost, or buck-boost modes, and the power flow way with the S_4 switch. Unidirectional power flow is preferred in buck-boost converter mode for the system to be analyzed. There are four operating modes since there are two voltage sources and whether these sources are in transmission or not. Since the switching modes and PWM signal strategies to be applied to the switches are explained in detail in the mentioned sources, there is no need for explanation in this study. A fixed frequency is applied to the keys. The output voltage V_0 to be obtained when the MIC works in buck-boost mode is given in Equation 6.

$$V_0 = \frac{d_1 V_1 + d_2 V_2}{1 - d_1 - d_2 + d_{12}} \tag{6}$$

The d_{12} used in Equation 6 indicates the time depending on the period in which both switches S_1 and S_2 are on. Assuming a lossless system, the output current I_0 from the input and output power equations is given in Equation 7.

$$I_0 = \frac{V_1 I_1 + V_2 I_2}{V_0} \tag{7}$$

The I_1 and I_2 currents given in Equation 7 represent the currents drawn from the first and second sources, respectively. I_1 and I_2 currents are found by multiplying the duty cycle ratios of switches S_1 and S_2, respectively, by the inductor current. Inductor and capacitor values of MIC can be found from the inductor current reference ripple value and the output voltage reference ripple value with Equation 8 and Equation 9, respectively.

$$\Delta_i = \frac{V_0[1-(d_1+d_2-d_{12})]}{L \cdot f} \tag{8}$$

$$\Delta_c = \frac{V_0(d_1+d_2-d_{12})}{R \cdot C \cdot f} \tag{9}$$

The parameters used in the simulation environment are given in Table III. The switching frequency is set at 20 kHz and the load at 5 Ω.

TABLE III
MIC CIRCUIT PARAMETERS

Parameter	Value
V_1	48 V_{DC}
V_2 *(mpp)*	24 V_{DC}
d_1	40 %
d_2	40 %
d_3	60 %
d_{12}	20 %
L	28 *mH*
C	4.32 *mF*
R	5 Ω
f	20 kHz
Δ_i	5 %
Δ_c	10 %

The output voltage, current, and power graph obtained in the simulation environment are given in Fig. 8. When the graphs are examined, it is seen that there are small differences according to the mathematical equations. The reason is that the circuit elements used in Simulink software are not ideal and have internal resistances.

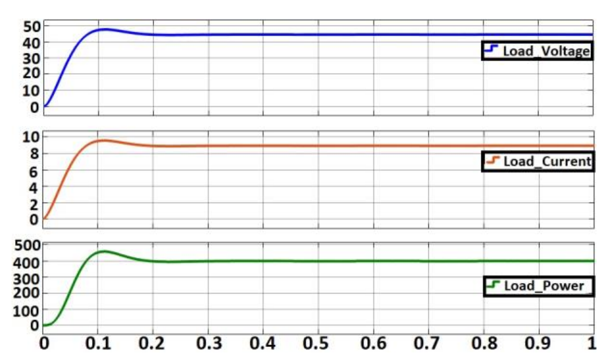

Fig. 8. The output voltage, current, and power graph

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Inductor voltage and inductor current graph are given in Fig. 9. When the inductor voltage graph is investigated, it is seen that it is proper for the PWM switching strategy used. A medium synchronous switching strategy is used in this study.

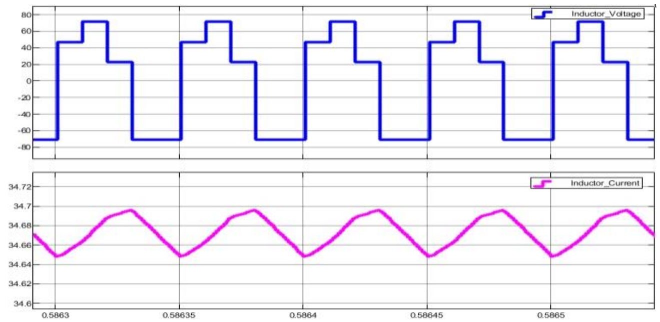

Fig. 9. Inductor voltage and current graph.

IV. Comparison of Topologies

Three different approaches have been chosen from MISO converter topologies. In the Matlab / Simulink simulation environment, small tolerance, accurate and stationary results were obtained according to the topology of each system. In the first topology, a separate converter circuit was used for each source, and this situation increased the number of circuit elements. In the second topology, the model with a single inductor common converter circuit is handled. The advantage of this topology is that it has a single inductor and a common converter circuit. However, unidirectional power flow is provided in both topologies. This situation can be considered as the disadvantage of topologies. In the third topology, bidirectional power flow is provided with the S_4 switch. In terms of this feature, the last topology is different from other topologies. All topologies are operated at a fixed frequency. The PWM signal strategy required for the switching of each topology is simple. Although a constant DC source has been selected as the input source in the simulation studies for all three topologies, in practice these sources are photovoltaic, wind, etc. it is important in that sources with different characteristics provide power to the load.

TABLE IV
TOPOLOGY COMPARISON

Parameter	Topology-1	Topology-2	Topology-3
Source values	same	different	different
Converter type	boost	buck/buck-boost	buck/boost
Power flow direction	unidirectional	unidirectional	bidirectional
Common inductance	no	yes	yes

V. Conclusions

Three different MIC topologies were analyzed and circuit models were installed in the simulation environment. When the topologies are compared, the two-input single-output buck-boost converter topology, which is the last used topology, came to the forefront especially in terms of providing bidirectional power. Considering that the use of renewable energy sources will increase to meet the energy needs in the future, it is predicted that new topologies will be needed to be created with DC-DC converter combinations with MIs or multiple outputs. Thus, it will be useful to work on the power flow control of MISO DC-DC converter systems using photovoltaic energy sources in future studies.

References

[1] Siemens® Databook, "Ferrites and Accessories", www.epcos.com.
[2] Ferroxcube® Databook, "Soft Ferrites and Accessories", www.ferroxcube.com.
[3] Magnetics® Databook, 2004 Magnetics Catalog, www.mag-inc.com.
[4] D. Dujić, F. Kieferndorf, and F. Canales, "Power electronic transformer technology for traction applications-An overview," Electronics. 2012.
[5] Y. J. Lee, A. Khaligh, and A. Emadi, "Advanced integrated bidirectional AC/DC and DC/DC converter for plug-in hybrid electric vehicles," IEEE Trans. Veh. Technol., 2009.
[6] Y. Du, S. Lukic, B. Jacobson, and A. Huang, "Review of high power isolated bi-directional DC-DC converters for PHEV/EV DC charging infrastructure," 2011.
[7] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of power converters in AC microgrids," IEEE Trans. Power Electron., 2012.
[8] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Grid-interfacing converter systems with enhanced voltage quality for microgrid application concept and implementation," IEEE Trans. Power Electron., 2011.
[9] Z. Zhao, M. Xu, Q. Chen, J. S. J. Lai, and Y. Cho, "Derivation, analysis, and implementation of a boost-buck converter-based high-efficiency PV inverter," IEEE Trans. Power Electron., 2012.
[10] B. Sri Revathi and M. Prabhakar, "Non-isolated high gain DC-DC converter topologies for PV applications – A comprehensive review," Renewable and Sustainable Energy Reviews. 2016.
[11] D. Burmester, R. Rayudu, W. Seah, and D. Akinyele, "A review of nanogrid topologies and technologies," Renewable and Sustainable Energy Reviews. 2017.
[12] Buning, E. A. (2010). Electric drives in agricultural machinery-approach from the tractor side. Journal of Agricultural Engineering, 47(3), 30-35.
[13] Hemetsberger F. A. (2003). An Investigation Of Power Quality Problems In A Remote Mine Site, M.S. Thesis, The University of Queensland.
[14] Mcmurray, W. (1970). U.S. Patent No. 3,517,300. Washington, DC: U.S. Patent and Trademark Office.
[15] J. L. Brooks, "Solid State Transformer Concept Development," 1980.
[16] E. R. Ronan, S. D. Sudhoff, S. F. Glover, and D. L. Galloway, "Application of power electronics to the distribution transformer," 2000.
[17] L. Yang, T. Zhao, J. Wang, and A. Q. Huang, "Design and analysis of a 270kW five-level DC/DC converter for solid-state transformer using 10kV SiC power devices," 2007.
[18] A. W. Lotfi and M. A. Wilkowski, "Issues and Advances in High-Frequency Magnetics for Switching Power Supplies," Proc. IEEE, 2001.
[19] M. Davari, S. M. Ale-Emran, H. Yazdanpanahi, and G. B. Gharehpetian, "Modeling the combination of UPQC and photovoltaic arrays with multi-input single-output DC-DC converter," 2009.
[20] R. Noroozian, M. Abedi, G. B. Gharehpetian, and A. Bayat, "On-grid and off-grid operation of multi-input single-output DC/DC converter based fuel cell generation system," 2010.
[21] Yalamanchili K. P., Ferdowsi M., Lu S., Xiao P., and Corzine K., "Derivation of Double-input DC-DC Power Electronic Converters", Electric Power Components and Systems, vol.39, no.5, 478-490, 2011.
[22] Archana N. and Anupamma K. I., "Multi-input Inverter for Hybrid Wind-Photovoltaic Standalone System", Second International Conference on Computing Methodologies and Communication, ICCMC 2018.

[23] L. Kumar and S. Jain, "A novel multiple-input DC-DC converter for electric vehicular applications," 2012.
[24] L. Kumar and S. Jain, "A multiple-input DC-DC converter for interfacing of battery/ultracapacitor in EVs/HEVs/FCVs," 2012.
[25] F. Akar, Y. Tavlasoglu, E. Ugur, B. Vural, and I. Aksoy, "A Bidirectional Nonisolated Multi-Input DC-DC Converter for Hybrid Energy Storage Systems in Electric Vehicles," IEEE Trans. Veh. Technol., 2016.
[26] Shetty S. N. and Raheman Md. A., "Design and Simulation of Dual Input DC/DC Converter", International Journal of Innovative Research in Electrical, Electronics, Instrumentation, and Control Engineering (IJIREEICE), National Conference on Advances in Electrical Engineering NCAEE, 2017.
[27] Shetty S. N. and Raheman Md. A., "Modelling of Dual Input DC/DC Converter for Hybrid Energy System", 2th IEEE International Conference on Recent Trends in Electronics Information & Communication Technology RTEICT, 2017.

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