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Experimental evaluation of the performance of virtual storage units in hybrid micro grids

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ABSTRACT

The work presented in this article proposes a new energy management algorithm for hybrid micro grids consisting of higher penetration of DC non-critical (NC) loads and renewable energy sources. The methodology suggested in this work is a rule based approach and tries to make the micro grids more autonomous. During generation deficits in the micro grids, the suggested control strategy proposes to make the hybrid micro grids self-dependent to a possible extent, without the incorporation of actual storage devices. Instead of using actual storage elements like the batteries or super capacitors, the projected approach uses virtual storage devices, like the DC electric springs for its functionality. The electric springs used in this work operate the DC NC loads in accordance with the voltage produced by the renewable sources, which in turn reduces the power import from the main grid during generation deficits in the micro grid. Further, the work presented in the due course only studies about the efficiency of the proposed algorithm by operating the DC NC loads as per the requirement, without intervening with the AC and DC critical loads operation. In order to test the robustness of the proposed methodology a scaled down hybrid micro grid is developed in the laboratory using dSPACE 1104 real time interface.

1. Introduction

Low voltage DC micro grids are gaining momentum due to certain advantages like reduced power losses and because of the advent of efficient power electronic conversion circuits [1]. In general, DC micro grids are used to feed sensitive loads, such as industrial and vehicular loads [2]. Furthermore, by putting DC apparatus in place the losses in the system also reduce. A case study has been conducted on a data center operating with DC system and it is said that the reduction in losses is about 10–20% [3]. The usage of DC micro grids in the presence of dispersed generation makes it possible to supply “super high quality power” to the consumers [4]. In order to prove the superior operation of the DC micro grids a study is conducted on a residence consisting of cogeneration along with loads, which are fed from the DC mains and it is proven that the system was able to remain in stable state even during load disturbances [5]. The authors in [6] also worked on super high quality power distribution using DC systems considering a bipolar grid structure and it is proven that the system withstands even for sudden load changes, short circuits, intentional islanding and many more.

A coordinated control strategy for DC micro grids consisting of a group of fluctuating energy sources is examined in [7]. The control strategy presented in [7] is tested in islanding, current control and dual modes and it is proven that the strategy works well for all the three cases. Further, in order to estimate the stability aspects of the DC micro grids in the presence of integrated wind and wave power generation systems a study is made in [8] where the authors proved that the DC micro grids are capable enough to deal with the wind and wave power integration. Also, the authors in [9] demonstrated that by using solar PV modules in the DC grids the overall efficiency of the system improves considerably. An energy management study on the DC micro grids considering different types of storages devices and higher penetration of renewable energy sources in presented in [10]. Lastly, the authors in [11] presented a droop control strategy for DC micro grids to enhance the flexibility of operation in the presence of battery storage facility.

Along with the application of DC grids, AC micro grids have also gained significance because of many reasons. The authors in [12] presented an approach for handling the energy storage facilities available in the AC micro grids consisting of super capacitors, battery storage and diesel generator units. Considering AC electric springs presented in [13] the authors in [14] presented a control strategy for reducing the dependence of AC micro grids on the main grid. The authors in [15] scheduled the storage units in the AC micro grids in the presence of intermittent energy sources in order to supply power to the loads in a

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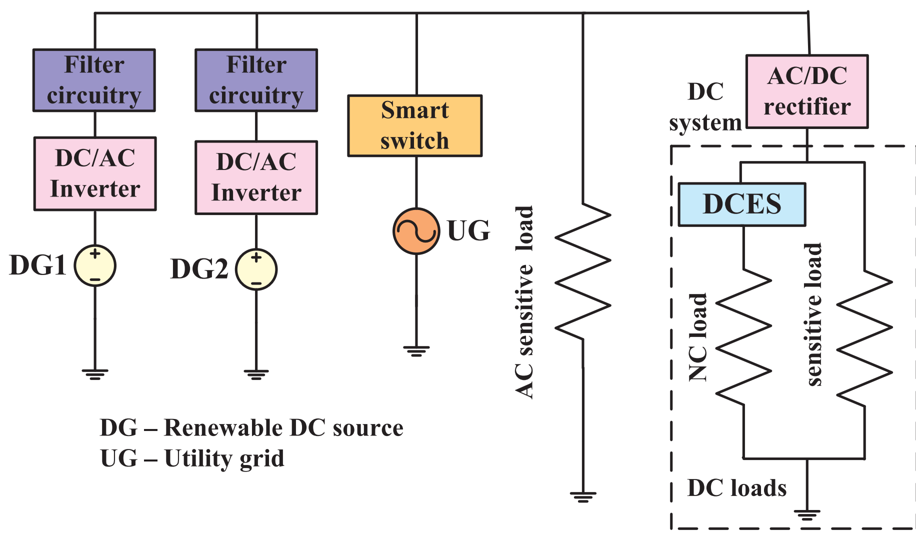

Fig. 1. Hybrid micro grid considered for the study.

reliable way. Further, a completely different methodology for integrating battery storage units into AC grids called as 'The AC battery' has been proposed in [16].

As a contradiction to the separate usage of AC & DC micro grids some of the works existing in the literature recommend the addition of DC network to the existing AC systems, so as to operate DC and AC loads present in the system [17]. The addition of DC network to the AC grids makes the system hybrid and hence it is called as hybrid or AC/DC network. Considering certain advantages of the hybrid micro grids researchers in the recent past tried to develop certain control strategies for effective energy management. The authors in [18] presented an energy management algorithm for hybrid AC/DC micro grids namely robust optimal power management scheme. The scheme presented in [18] schedules the renewable energy sources in an optimal way and tries to improve the health of the batteries existing in the system. Further, the authors in [19] presented an emergency energy management strategy for industrial hybrid micro grids. The authors in [20] optimized the generation of the fluctuating energy sources in AC/DC grid system by combining cuckoo search and Nelder – Mead algorithms.

Furthermore, a coordinated control approach for hybrid micro grids is presented in [21]. The work presented in [21] focuses on operating the hybrid grids in a stable way in both islanded and grid tie modes. Similar to the work presented in [21] the authors in [22] presented a control scheme for AC/DC micro grid in a smart building to reduce the dependence on main grid. Going little ahead towards the autonomous operation of the hybrid micro grids the authors in [23] presented a control algorithm, based on fuzzy sets and the operation of the battery unit/s existing in the standalone micro grids for effective load management and also to achieve better reliability by assuring proper power flow between AC and DC networks. The authors in [24] presented a multi objective approach using Particle swarm optimization to schedule the hybrid micro grids consisting of renewable energy sources and batteries. The authors proposed an efficient algorithm by maintaining state of charge of batteries in an effective way. In the recent past a new type of methodology to deal with the nexus of water in rural areas powered by autonomous AC/DC micro grids is presented in [25]. Apart from the different methodologies presented on AC/DC micro grids a simpler methodology known as the droop control for hybrid micro grids is proposed in some of the articles suggested in [26,27].

Differing from the articles presented on hybrid, AC and DC micro grids a new type of smart grid technology known as DC electric springs (DCES) has been presented to the literature in [28]. The DCES presented in [28] acts like a virtual storage unit and has an ability to manage power in the micro grids. This DCES is analogous to mechanical spring in its working and as it is used in DC circuits to control DC non critical loads it is named as DC electric spring.

By going through the works presented in [1–28] it is clear that most of the researchers focused on developing energy management solutions to the micro grids. Therefore, it can be concluded that there is much to explore in the field of hybrid micro grids. As an extension to the works presented in the literature, this paper tries to propose a different energy management algorithm based on the rules framed for a micro grid system consisting of higher penetration of DC loads and lesser penetration of AC loads. The proposed study aims at making the hybrid micro grid structures more autonomous and less dependent on main grid by using virtual storage unit/s like the DC electric springs instead of using actual storage units like the batteries, which is possibly the first attempt.

2. System description and basics of DCES

2.1. System description

In order to test the effectiveness of the presented rule based approach a hybrid micro grid system consisting of two DC renewable power sources, one utility grid(UG) connection point and different types of loads is considered for the study. As shown in the Fig. 1 it can be understood that the considered micro grid structure consists of DC renewable generators, conversion circuits and more importantly AC & DC loads. The utility grid considered in this study is expected to support the system during generation deficits in the micro sources. The AC loads considered in this work are voltage sensitive (critical) loads and the total power requirement for the AC loads considered is less in comparison to the DC loads present in the system. Further, the DC loads present in the system are classified as voltage sensitive and insensitive loads. The voltage sensitive loads are commonly referred as critical loads and the voltage insensitive loads are referred to as Non Critical (NC) loads.

In this work the energy management algorithm schedules the NC loads present in the system using DCES, which act like the virtual storage unit. The NC loads considered in this work are constant resistance loads like the water heaters, space heaters and lighting systems used in parking lots [28]. Unlike the NC loads suggested in the literature the NC loads considered in this work are capable of operating at relatively higher voltage tolerance levels. In this work the tolerance level of voltage considered for NC loads is about 20% from their rated value. Taking the advantage of the voltage insensitiveness of the loads the NC loads present in the system are operated in power saving mode by

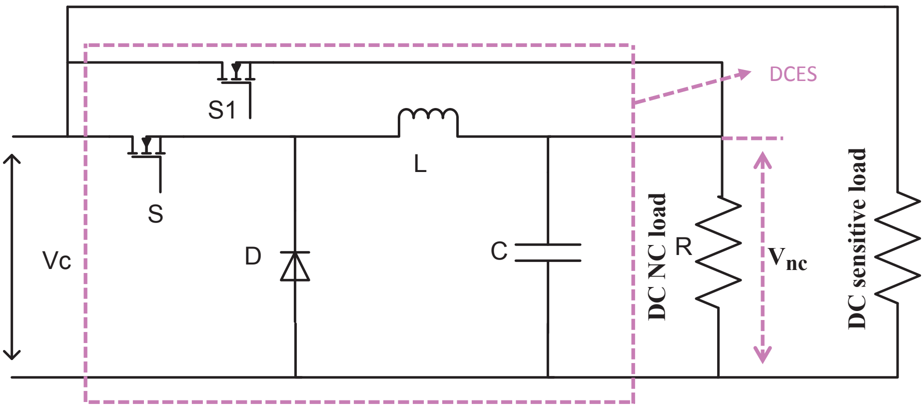

Fig. 2. Connection diagram of the DCES or the virtual storage unit [28].

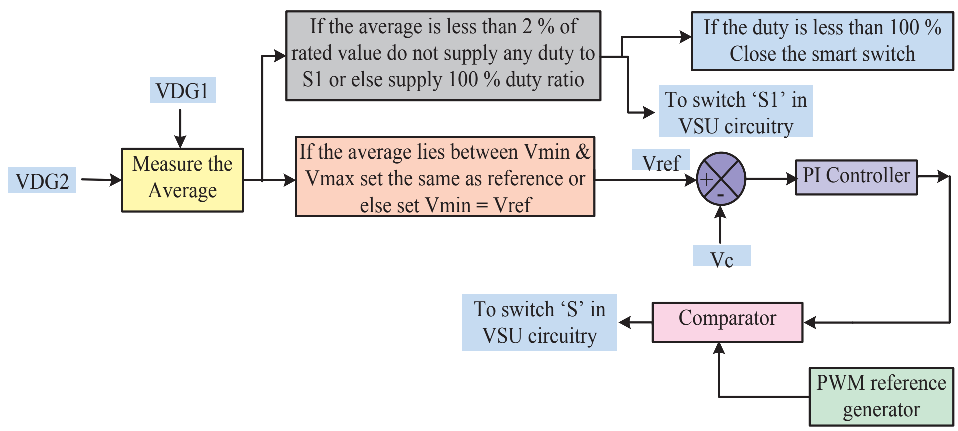

Fig. 3. Control strategy proposed for the study.

Table 1
System description.

Description	System Rating
Rated AC voltage of the system	80 V
Power rating of AC load	8 W
Rated DC voltage of the system	80 V
Power rating of the DC voltage sensitive load	14 W
Maximum rating of the DC NC load	24 W
DC output voltage of the DGs (programmable sources)	80 V
Maximum current rating of the considered sources	12 A

supplying an underrated voltage to them as per the requirement. The voltage supplied to the NC loads is decided based on the voltage produced by the renewable generators. It may be noted that the objective of the work is to estimate the performance of the system by only scheduling DC noncritical loads, without disturbing the AC as well as DC sensitive loads.

2.2. Basics of DC electric spring and its connection with NC load

DC electric spring (or) the virtual storage unit is analogous to mechanical spring and the detailed explanation about the interpretation with the mechanical spring can be obtained from [28]. Fig. 2, depicts the detailed architecture of the DCES which consists of semiconductor devices and other passive elements as shown. The operation of the spring circuitry is as follows. During the normal operating conditions i.e. whenever there is no necessity to conserve any power in the system the switch 'S1' is supplied with almost 100% duty ratio which means that both the voltage sensitive and insensitive loads come in parallel to each other and there will be no suppression in the voltage supplied to the NC loads. This particular mode in which the spring operates without suppressing the voltage is called as normal operating mode.

Whenever there is a pressing need to control the voltage supplied to the NC load (R) the switch 'S1' is thrown open and a suitable duty ratio is applied to switch 'S' so that the voltage is as per the requirement and this mode of operation is termed as voltage suppression mode of the spring. The values of the inductor (L) and capacitor(C) presented in Fig. 2 are designed as per the methodology followed for the buck converter. Now, by considering the operation of DCES it can be said that during the voltage suppression operation of the spring it conserves some power because, the power consumption in the constant resistance loads is completely dependent on the voltage supplied. This reduction in power directly reduces the power served by the supply system and this reduction was possible only because there is a reduction in the power requirement from the load side which is due to the presence of DCES. Therefore, it can be interpreted that this power electronic circuitry in one way is able to act like a storage element, which reduces the demand on the system, whenever required. It is because of this virtual ability to act like a storage device the DCES can also be called as the virtual storage unit (VSU).

3. Problem formulation

The specific objective of this work is to make the hybrid micro grid more autonomous by making it less dependent on the utility grid by using virtual storage units (VSU) without using any real time storage devices like the batteries or fuel cells. The power balance equation pertaining to the Fig. 1 is as follows.

$$P_{DG1} + P_{DG2} + P_{UG} = P_{ACS} + P_{AC}^{Eq} \tag{1}$$

where $P_{DG1} and P_{DG2}$ is the equivalent AC power supplied by the

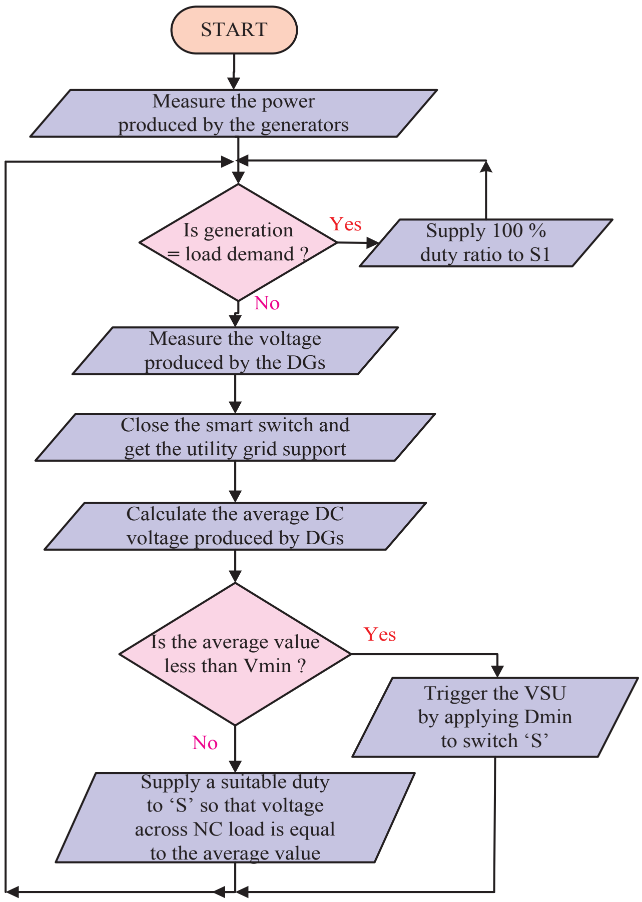

Fig. 4. Flow chart of the rule based energy management algorithm.

renewable sources, P_{UG} is the AC power supplied by the utility grid, P_{ACS} is the power consumed by the voltage sensitive AC load, P_{AC}^{Eq} is the equivalent AC power consumed by the DC loads present in the micro grid.

In order to make the hybrid grid more autonomous it is essential to make it self-sufficient, which is possible only if it relays less on the utility grid. Hence, to focus more on this possible move the Eq. (1) has to be modified so as to make it more suitable for the said objective and the same is depicted in Eq. (2).

$$\text{Min. } P_{UG} = P_{ACS} + P_{AC}^{Eq} - (P_{DG1} + P_{DG2}) \tag{2}$$

From Eq. (2) it has to be understood that the reduction in power served by the main grid can only be reduced by altering the P_{AC}^{Eq}. This is because the power served to the AC critical loads cannot be altered and also the power produced by the renewable sources also remains the same for the considered scenario. The equivalent AC power is a combination of the Critical (sensitive) and NC load power, of which the voltage insensitive load power can be varied by pressing VSU into action. Further, it may also be kept in mind that power consumption of AC sensitive loads is also left unaltered along with the power produced by the distributed generators, which is also not in the ambit of the presented control algorithm.

From Eq. (2) it can be understood that the equivalent AC power is dependent on the power pattern of the DC loads and hence the inequality pertaining to the same is presented in Eq. (3).

$$P_{AC}^{Eq} \propto P_{DC} \tag{3}$$

P_{DC} is the total power consumed by the DC critical and NC loads. The power consumption pattern of the DC loads can once again be represented as an equation and the same is as shown in Eq. (4).

$$P_{DC} = P_{SL} + P_{NC} \tag{4}$$

$P_{SL} and P_{NC}$ is the power consumption pattern of the DC sensitive and NC load respectively. Further, the power consumption of the DC NC load can be further written as follows.

$$P_{NC} = \frac{V_{NC}^2}{R} \tag{5}$$

V_{NC} is the voltage across the DC NC load and R is the resistance of the voltage insensitive load.

The power equation presented in Eq. (5) is true only if the switch 'S1' is kept closed and further the Eq. (5) stand modified during the voltage suppression function of the VSU and the same is presented in Eq. (6)

$$P_{NC}^{VS} = \frac{(DV_c)^2}{R} \tag{6}$$

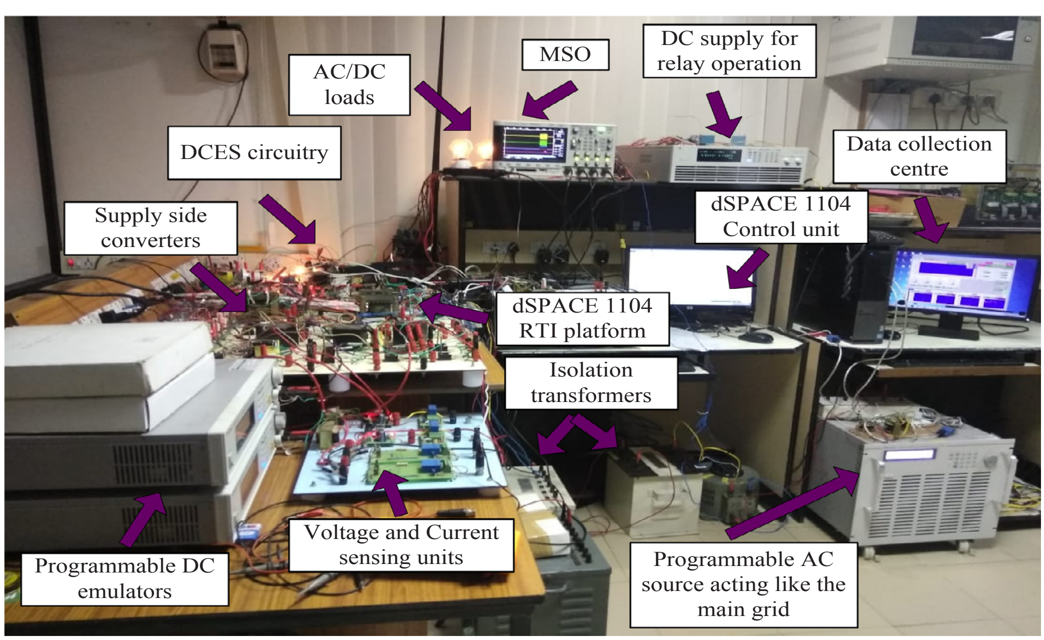

Fig. 5. Laboratory scale hybrid micro grid developed for the study.

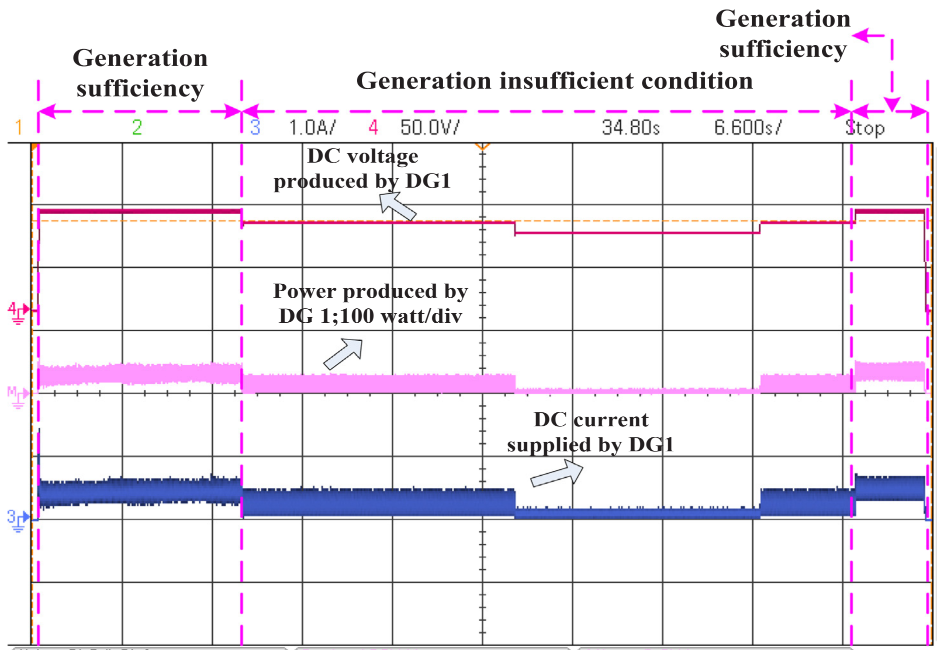

Fig. 6. Output DC parameters of the DG1.

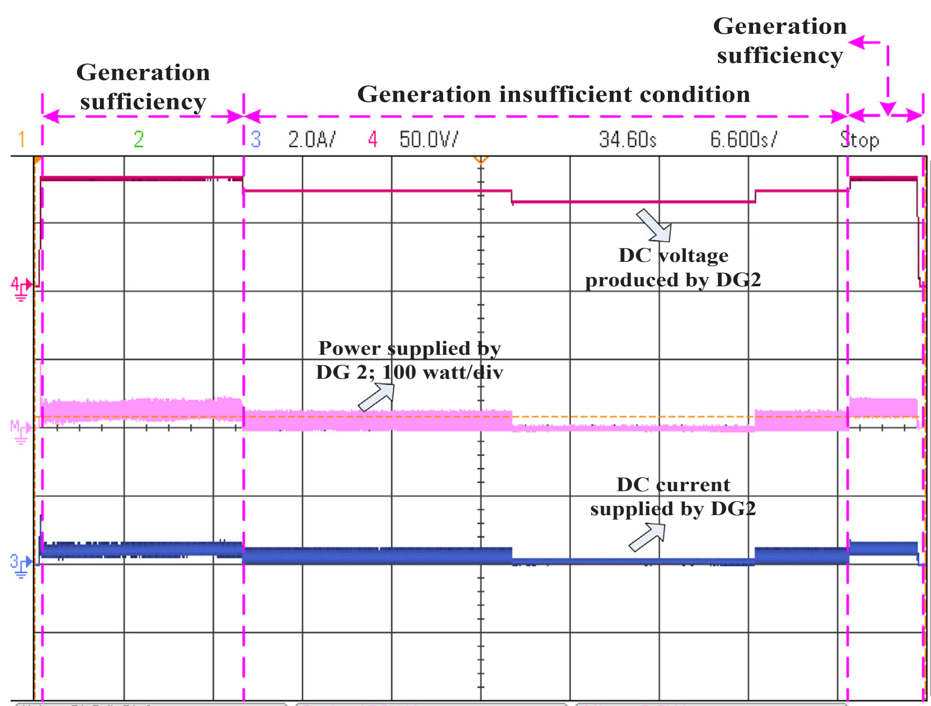

Fig. 7. Output DC parameters of the DG2.

P_{NC}^{VS} is the power pattern of the DC NC load during the voltage suppression action of VSU, D is the duty ratio applied to switch 'S' and V_c is the voltage appearing the sensitive DC load. The duty ratio applied to the switch is decided by the energy management algorithm and is constrained as presented in Eq. (7)

$$D_{min} < D < D_{max} \tag{7}$$

The minimum value of the duty that has to be applied to 'S' is decided based on the minimum permissible voltage at which the NC load is supposed to operate. By looking at the constraint imposed on the duty ratio it can be held that the overall power consumption on the DC side reduces which subsequently reduces the equivalent AC power and the same is show cased in Eqs. (8), (9) and (10).

$$P_{NC} \geq P_{NC}^{VS} \tag{8}$$

$$P_{DC} \geq P_{DC}^{VS} \tag{9}$$

$$P_{AC}^{Eq} \geq P_{AC}^{Eq(VS)} \tag{10}$$

The superscript *VS* represents the parameter during voltage suppression mode of the VSU. Also, due to the voltage suppression action of DCES the power consumption profile of the utility grid also changes and the same is presented in Eq. (11).

$$P_{UG}^{Eq(VS)} = P_{ACS} + P_{AC}^{Eq(VS)} - P_{DG} \tag{11}$$

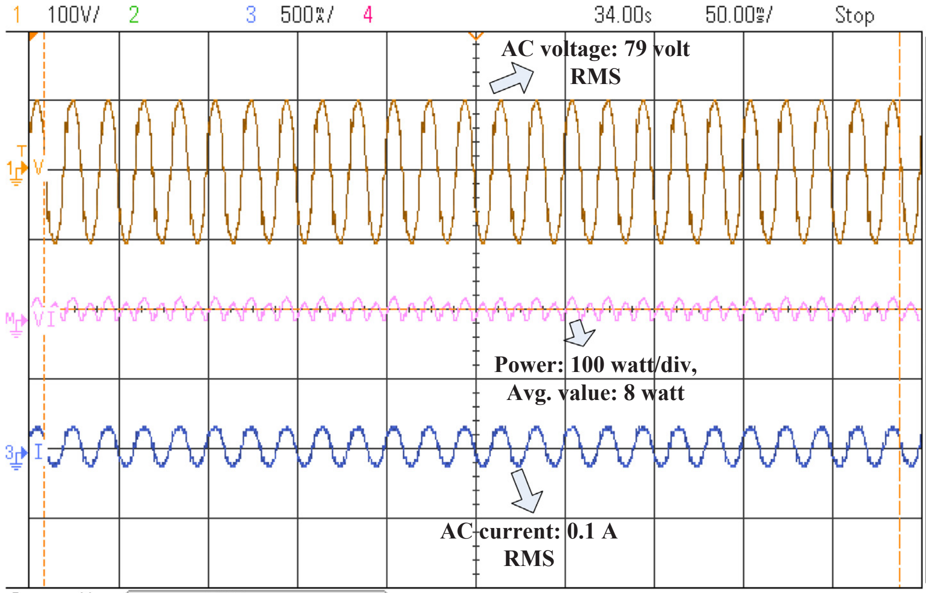

Fig. 8. AC sensitive load parameters.

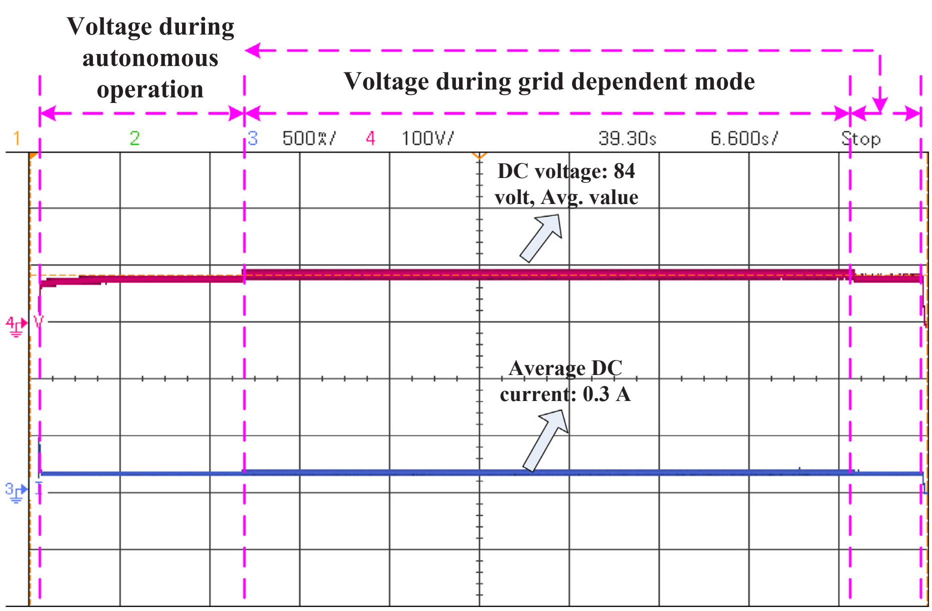

Fig. 9. Voltage and current supplied to the DC sensitive load.

P_{DG} is the total AC power supplied by the renewable sources. By subtracting Eqs. (2) and (11) an inequality condition pertaining to the changed grid power can be achieved and the resultant equation post subtraction is as presented in Eq. (12).

$$P_{UG} - P_{UG}^{Eq(VS)} = P_{AC}^{Eq(VS)} - P_{AC}^{Eq(VS)} \tag{12}$$

From Eq. (12) an inequality pertaining to the grid power can be derived and the same is presented in Eq. (13).

$$P_{UG} \geq P_{UG}^{Eq(VS)} \tag{13}$$

From Eq. (13) it can be said that the power delivered by the utility grid during the voltage suppression mode of the VSU is less in comparison to its normal mode of operation.

4. Proposed control strategy for the NC loads

In order to effectively schedule the DC NC loads using the VSU a rule based approach presented in [29] is used in this work with some modifications to make it suitable for the hybrid micro grid considered for the study. In this work, the suggested algorithm is implemented on a hybrid micro grid structure, which consists of a predominant share of DC loads. Fig. 4 depicts the control structure of the energy management algorithm considered for the study, where Vmin represents the minimum permissible value of voltage that has to be applied to the NC load and Dmin is the minimum prescribed level of duty ratio that has to be supplied to 'S', during its operation. Figs. 3 and 4 depicts the control strategy and energy management algorithm presented for the study. The control algorithm and the strategy proposed operate the NC loads at required power saving modes, based on the voltage produced by the DGs. In the considered case study, the only left out option to manage the energy is by using the VSU present in the system.

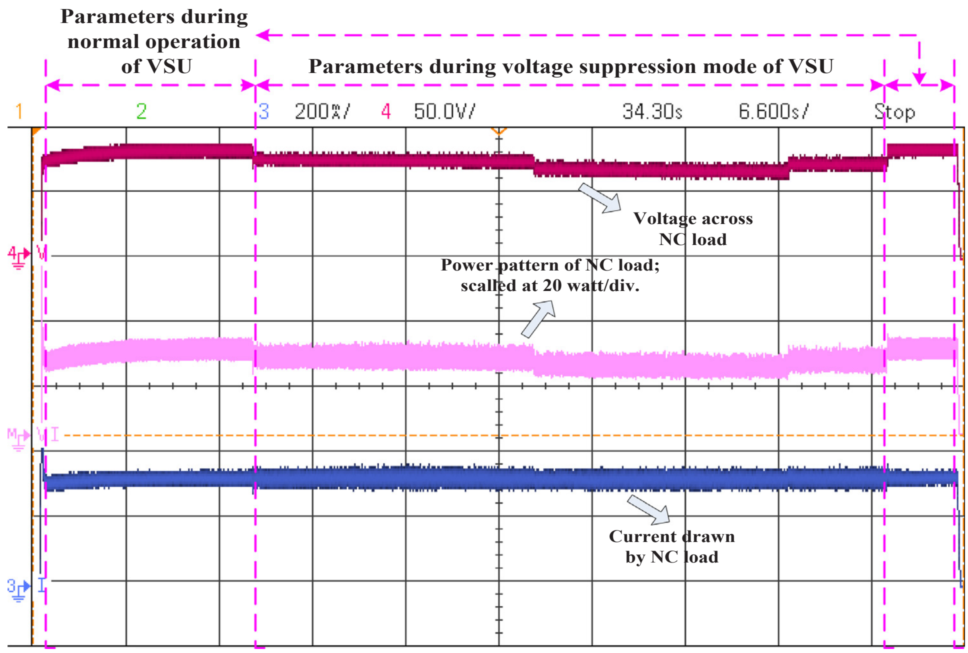

Fig. 10. Parameters of the NC load.

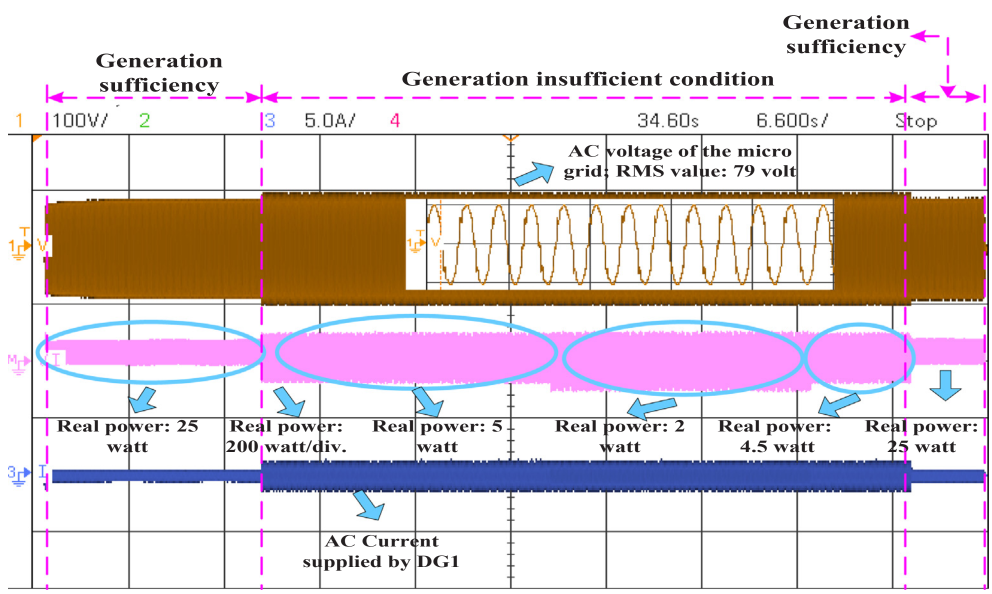

Fig. 11. AC power supplied by the DG1.

5. Experimental results and discussion

In order to prove the effectiveness of the presented algorithm, the micro grid structure presented in Fig. 1 is developed in the laboratory as per the facilities available and the details are as depicted in Table 1.

Table 1 presents the system rating considered for the study. The experimental models developed for the study are based on the availability of the resources in the laboratory and hence it can be treated as a scaled down version. In the conducted experimental study, two programmable DC voltage sources are considered as DG's in the study. Fig. 5 projects the laboratory scale hybrid micro grid developed for the study.

In order to study the effectiveness of the proposed algorithm both the programmable DC sources are preprogrammed to operate for a total time of 65 s. Out of the 65 s considered for the study the DC sources are expected to generate the rated power (sufficient to feed all the loads losses) only during the first 15 s and last 5 s. Therefore, it can be understood that for most of the time the main grid is expected to support the system because of the unavailability of actual storage devices in the micro grid. The utility grid considered in the experimentation is nothing but the programmable AC source depicted in Fig. 5. The AC source can be programmed to produce a maximum 1-phase voltage of 300 V and 3 A current. In order to achieve synchronism with the renewable sources the AC source is pre-programmed to produce an output voltage of 80 V, during generation deficits. The output parameters of the DC sources are pre-programmed to mimic the behavior of the actual renewable sources and the same is presented in Figs. 6 and 7.

From the Figs. 6 and 7 it can be understood that the voltage and current supplied by the DGs is not constant and hence there is a requirement for the utility grid to support the micro grid during generation deficits. During generation deficits of the micro sources the UG is expected to compensate the deficit power, so that there will not be

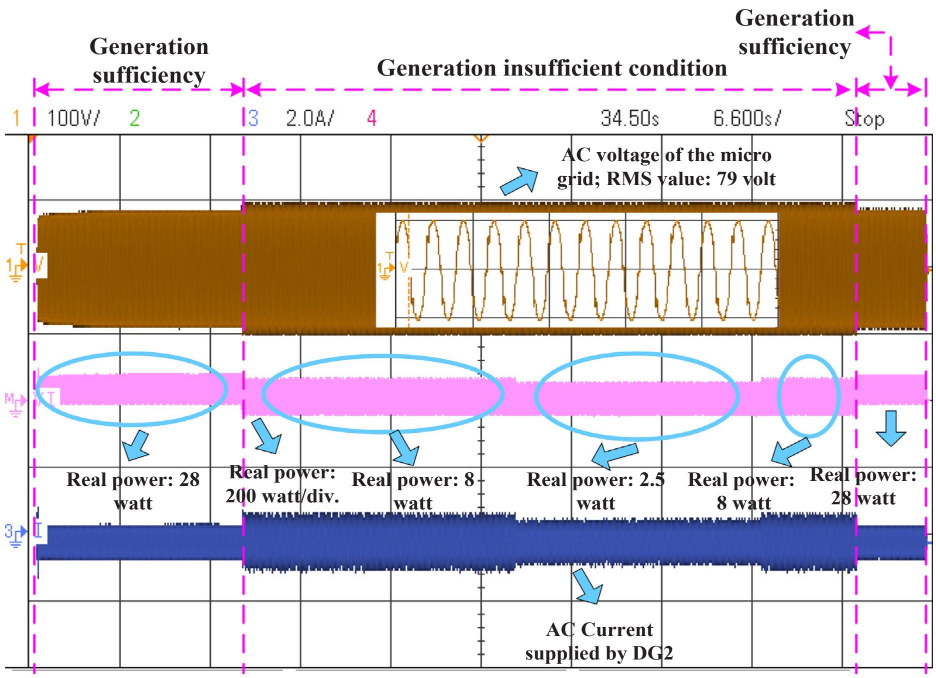

Fig. 12. AC power supplied by the DG2.

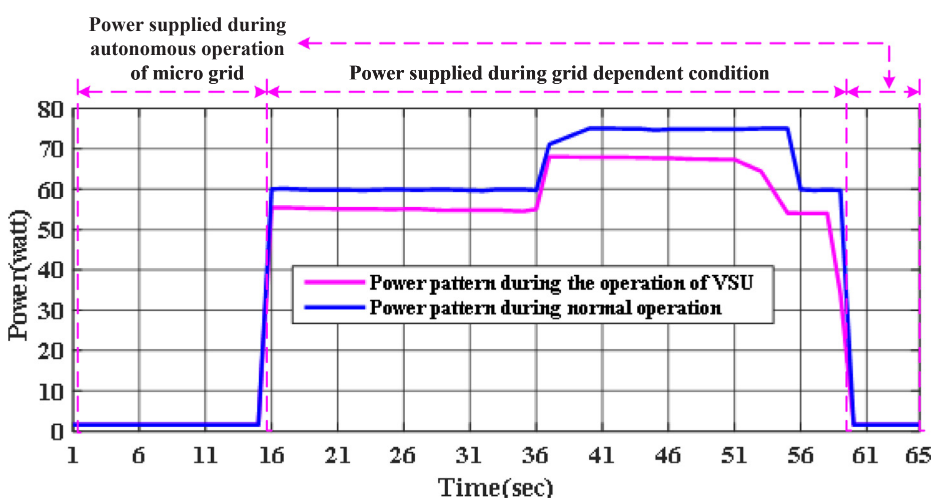

Fig. 13. Power supplied by the utility grid.

Table 2
Energy served by the utility grid.

Energy served by the utility grid in the presence of VSU	1717.2 W sec
Energy served by the main grid during normal operating conditions	1922.8 W sec
Saving achieved in energy	205.6 W sec
% Saving achieved	11(approx.)

any interruption to the power supplied to the AC & DC sensitive loads. A brief pattern of the voltage supplied to the AC voltage sensitive load during the grid support mode is presented in Fig. 8. It may be understood that almost the same value of voltage is supplied throughout the run time. From Fig. 8 it can also be concluded that the voltage appearing across the AC load is nothing but the voltage of the AC bus.

Along with the AC sensitive loads it is also essential to supply better regulated voltage to the DC sensitive load and therefore the level of voltage supplied to the DC sensitive load is also held constant throughout the run. Fig. 9 shows the constant voltage and the current pattern of the DC sensitive load. As the voltage and current are maintained constant, the power consumption will be also be held at 24 W, which is nothing but the rated value. Further, as per the presented algorithm, it is also important to operate the NC loads as per the voltage produced by the DGs. The different parameters of the NC loads attained by operating the VSU are presented in Fig. 10.

Also, the AC power supplied by the DC sources measured at the output end of the inverter is presented in Figs. 11 and 12 respectively. The real power values presented in Figs. 11 and 12 are obtained by calculating the average value over a certain number of cycles.

In order to prove the efficiency of the presented algorithm in making the micro grid structure more autonomous, a study is conducted on the system by making the VSU in-operational. In this case even during grid support mode the NC loads are operated at full rated voltage level and a comparative study of the power, current and other vital parameters in the presence and absence of the VSU is presented.

Fig. 13 presents the power supply pattern of the UG in the presence and absence of the VSU. The data presented in Fig. 13 is obtained from the data logger of the AC programmable source, which is acting like the main grid. By observing the power pattern of the UG it can be established that the share of power from the UG is lesser during the operation of spring. Further, the energy served by the UG is also evaluated and the same is presented in Table.2.

By looking at Table. 2 it can be understood that the percentage saving in energy achieved due to the action of VSU is about 11%, which is encouraging. Therefore, it can be established that by using the virtual storage units like the DCES in hybrid micro grid systems consisting of higher penetration of DC constant impedance loads, the micro grid system can be made little more autonomous.

6. Conclusion

The results obtained from the study prove that the algorithm used for the study is certainly efficient in making the micro grids autonomous. From the study it can be said that the proposed control strategy can reduce the power import from the main grid by 11%, which is satisfactory. The reduction achieved is completely subjective and may vary from case to case. In this work, the effectiveness of the algorithm is tested by considerably reducing the power supplied by the renewable sources which means that the algorithm is efficient enough to tackle any kind of power deficit conditions. Further, in this work only virtual storage units are used to achieve certain benefits, but the authors are of the opinion that there is a necessity to develop certain other rule based approaches which are capable enough to handle both actual and virtual storage units. Also, it is important to bring more number of loads which can operate at higher voltage tolerance levels, so that the algorithms of this kind may gain significance. Apart from the proposed energy management algorithm, it is also important to analyze the economic and reliability aspects of the electric spring, which can also be treated as the future scope of this work.

Declaration of Competing Interest

The authors hereby declare no conflict of interest.

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References:-

[1] Anand S, Fernandes BG, Guerrero JM. Distributed control to ensure proportional load sharing and improve voltage regulation in low voltage DC microgrids. IEEE Trans Power Electron 2013;28(4):2013.
[2] Eghtedarpour N, Farjah E. Control strategy for distributed integration of photovoltaic and energy storage systems in DC micro-grids. Renewable Energy 2012;45:96–110.
[3] DC power production, delivery and utilization. EPRI white paper; Jun, 2006.
[4] Kakigano H, Miura Y, Ise T, Uchida R. DC voltage control of the DC micro-grid for super high quality distribution. IEEE Power Conversion Conference-Nagoya 2007;PCC'07:518–25.
[5] Kakigano H, Miura Y, Ise T, Momose T, Hayakawa H. Fundamental characteristics of DC microgrid for residential houses with cogeneration system in each house. IEEE power and energy society general meeting-conversion and delivery of electrical energy in the 21st century. 2008. p. 1–8.
[6] Kakigano H, Miura Y, Ise T. Low-voltage bipolar-type DC microgrid for super high quality distribution. IEEE Trans Power Electron 2010;25(12):3066–75.
[7] Prakash S, Mishra S, Padhy NP. Coordinated control of a grid connected DC microgrid with multiple renewable sources. IEEE PES Asia-Pacific power and energy engineering conference APPEEC. 2016. p. 520–5.
[8] Lu SY, Wang L, Lo TM, Prokhorov AV. Integration of wind power and wave power generation systems using a DC microgrid. IEEE Trans Ind Appl 2015;51(4):2753–61.
[9] Rauf S, Wahab A, Rizwan M, Rasool S, Khan N. Application of Dc-grid for efficient use of solar PV system in smart grid. Procedia Comput Sci 2016;83:902–6.
[10] Liu B, Zhuo F, Zhu Y, Yi H. System operation and energy management of a renewable energy-based DC micro-grid for high penetration depth application. IEEE Trans Smart Grid 2015;6(3):1147–55.
[11] Li Y, He L, Liu F, Li C, Cao Y, Shahidehpour M. Flexible voltage control strategy considering distributed energy storages for DC distribution network. IEEE Trans Smart Grid 2017.
[12] Hassan MU, Humayun M, Ullah R, Liu B, Fang Z. Control strategy of hybrid energy storage system in diesel generator based isolated AC micro-grids. J Electr Syst Inf Technol 2018;5:964–76.
[13] Hui SY, Lee CK, Wu FF. Electric springs—a new smart grid technology. IEEE Trans Smart Grid 2012;3(3):1552–61.
[14] Cherukuri SHC, Saravanan B. A novel energy management algorithm for reduction of main grid dependence in future smart grids using electric springs. Sustain Energy Technol Assess 2017;21:1–12.
[15] Liu X, Xu W. Economic load dispatch constrained by wind power availability: a here-and-now approach. IEEE Trans Sustain Energy 2010;1(1):2–9.
[16] Helling F, Glueck J, Singer A, Pfisterer HJ, Weyh T. The AC battery – a novel approach for integrating batteries into AC systems. Int J Electr Power Energy Syst 2019;104:150–8.
[17] Zhao C, Dong S, Gu C, Li F, Song Y, Padhy NP. New problem formulation for optimal demand side response in hybrid ac/dc systems. IEEE Trans Smart Grid 2018;9(4):3154–65.
[18] Hosseinzadeh M, Salmasi FR. Robust optimal power management system for a hybrid AC/DC micro-grid. IEEE Trans Sustain Energy 2015;6(3):675–87.
[19] Miao M, Li Y, Wang Z, Ouyang L, Liu F, Lee KY, Tan Y. An emergency energy management for ac/dc micro-grids in industrial park. IFAC-Papers OnLine. 2018. p. 251–5.
[20] Kumar JS, Raja SC, Nesamalar JJD, Venkatesh P. Optimizing renewable based generations in AC/DC microgrid system using hybrid Nelder-Mead–Cuckoo Search algorithm. Energy 2018;158:204–15.
[21] Liu X, Wang P, Loh PC. A hybrid AC/DC microgrid and its coordination control. IEEE Trans Smart Grid 2011;2(2):278–86.
[22] Wang Y, Li Y, Cao Y, Tan Y, He L, Han J. Hybrid AC/DC microgrid architecture with comprehensive control strategy for energy management of smart building. Int J Electr Power Energy Syst 2018;101:151–61.
[23] Hosseinzadeh M, Salmasi FR. Power management of an isolated hybrid AC/DC micro-grid with fuzzy control of battery banks. IET Renew Power Gener 2015;9(5):484–93.
[24] Indragandhi V, Logesh R, Subramaniyaswamy V, Vijayakumar V, Siarry P, Uden L. Multi-objective optimization and energy management in renewable based AC/DC microgrid. Comput Electr Eng 2018.
[25] Niknejad P, Venneti S, Vasefi M, Jeffryes C, Barzegaran MR. An electrochemically assisted AC/DC microgrid configuration with waste water treatment capability. Electr Power Syst Res 2018;162:207–19.
[26] Akhter F, Macpherson DE, Harrison GP, Bukhsh WA. DC voltage droop control implementation in the ac/dc power flow algorithm: combinational approach. 11th IET International conference on AC and DC power transmission. 2015. p. 1–6.
[27] Rasoolzadeh A, Salmasi FR. Reduced-order dynamic model for droop-controlled inverter/converter-based low-voltage hybrid AC/DC microgrids–part 1: AC submicrogrid. IET Smart Grid 2018;1(4):123–33.
[28] Cherukuri SHC, Saravanan B, Swarup KS. Analysis of DC Electric springs in the micro grid system consisting of fluctuating Energy sources. Energy Procedia 2016;90:114–23.
[29] Cherukuri SHC, Saravanan B, Swarup KS. A new control algorithm for energy conservation from main grid during generation intermittence in the micro grids using A.C electric springs. IEEE conference on 21st century energy needs – materials, systems and applications (ICTFCEN). 2017. p. 1–6.