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# Inertia Emulation with Concept of Virtual Supercapacitor for Islanded DC Micro-grid

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## Abstract

The expansion of renewable energy sources (RESs) and the advances in power electronics have led to more attention being paid to DC micro-grids (DCMGs). DCMGs enable the exploitation of all renewable energy potentials. Along with the advantages of RESs and DCMGs, the use of RESs is associated with the challenges of absence or lack of inherent inertia. Inertia in DCMGs plays an important role in reducing the voltage changes under the destructive events such as the load change and power change. Therefore, by applying energy storage systems (ESSs) in DCMGs and inertia emulation, the mentioned challenges can be overcome. The proposed control scheme is implemented based on the concept of the virtual supercapacitor in the inner control loop of the ESS interface dual-half-bridge (DHB) converter with DCMG to emulate the inertia. Due to the high efficiency, electrical insulation, inherent soft switching, and the requirement for a smaller filter, the DHB converter is used. Finally, a DCMG is simulated in MATLAB/Simulink. The simulation results obtained show the efficiency and flexibility of the proposed scheme in terms of inertia emulation.

**Keywords:** *Virtual inertia, Virtual supercapacitor, Energy storage systems, Dual-half-bridge converter.*

## 1. Introduction

The rising concerns about the environmental impact of fossil fuel along with the benefits of renewable energy sources (RESs) have led the researchers to focus on RESs [1]. Therefore, micro-grids (MGs) have been studied as a suitable alternative. DC micro-grids (DCMGs) are suitable for using energy sources (e.g. photovoltaic system, batteries) and DC loads (e.g. data centers, electric vehicle (EV) charging stations) [2]. Due to the absence or lack of inherent inertia, new challenges have been created for DCMGs. With a lack of inertia, a DCMG may experience an undesirable voltage deviation. In order to solve this problem, the concept of virtual inertia and emulation of inertia has been expressed. The research on inertial emulation in DCMGs is expanding. In [3], a control scheme for inertial emulation has been simulated. However, this scheme does not provide grid inertia in the island mode. Modeling of DC machines can be used to emulate inertia in DCMGs. In [4], using the concept of separately excited dc machines, the required inertia of the grid can be provided. According to the desired specifications of the compound dc machine in [5], this machine has been modeled. However, these control schemes are very sophisticated. In [6, 7], a virtual inertia strategy has been proposed in order to improve a DC bus voltage. However, isolated converters can be used for the efficiency and battery protection. A virtual inertia control strategy has been investigated by adding an inertia control loop in [8] in order to provide inertia for battery-based island DCMGs. However, this method enters voltage differential into the control strategy, which easily leads to high-frequency disturbances. A control strategy under the concept of VDCM has been proposed using the equations governing the separately excited real DC machine but the dynamic equations governing the synchronous machine have been used [9]. Real supercapacitors can be used for inertia emulation due to their rapid response. However, limited nominal power delivery time, higher initial costs, and high self-discharge rates reduce its attractiveness and efficiency [10]. The use of batteries and power electronic converters (PECs) as a unit of inertia imitation has been recommended due to its low discharge and low battery cost [11]. In this paper, a new method is proposed to create virtual inertia in DCMGs by presenting a virtual supercapacitor control scheme. This scheme provides the required inertia of DCMGs using the governing equations of the capacitor. With further analysis, the dual-half-bridge (DHB) converter has been used as a battery and grid interface power converter. The advantages of this type of converter include high efficiency, high reliability, high power density, electrical insulation, low device stress, low noise, inherent soft switching, and the requirement for a smaller filter [12]. In order to evaluate the performance and efficiency of the proposed design, various tests are performed on DCMG. Therefore, the purpose of presenting this article is as follows:

- Improving the stability of DC bus voltage by enhancing the inertia of DCMG.
- Inertia emulation by applying virtual supercapacitor strategy based on DHB converter.
- Integration of the concept of virtual capacitors and ESS as a virtual supercapacitor.

The remainder of this paper is organized as what follows. Section 2 describes the structure of DCMG. Section 3 describes the concept of virtual inertia emulation (VIE) and supercapacitor modeling. Section 4 describes a virtual supercapacitor. Finally, in sections 5 and 6, the simulation results and the conclusions of the article are presented.

## 2. Structure of DCMG

In this section, in order to evaluate the performance of the virtual supercapacitor unit, a DCMG with power generating units, DC load, and ESS with DHB converter is considered as the unit of inertia emulation. Due to the high efficiency of the wind and solar energies, wind turbine (WT) and photovoltaic (PV) cells are used as the main manufacturers. Also due to the variable nature of the wind and solar energy sources, the fuel cell (FC) unit is intended to provide part of the total load. A schematic diagram of this DCMG is shown in figure 1. PV panels with irradiation of 1000 w/m$^2$ and a temperature of 25 ℃ can produce a maximum rated power of 6 kW. This unit is connected to the DC bus by a boost DC-DC power converter. WT is based on a permanent magnet synchronous generator (PMSG) with a rated power of 4.5 kW. First, using a three-phase bridge, the output voltage of this unit is converted to DC, and then connected to the DC bus by a boost DC-DC power converter. The fuel cell (FC) unit delivers 3 kW with current controllers and power management by the Boost converter. The battery pack consists of two 48 V series batteries. This unit adjusts the input and output power according to the DC bus voltage, keeps the conditions, and controls the charge and discharge rate of the battery pack. This unit can support the system with a nominal power exchange of 3 kW. The load unit consists of a DC load of 13.5 kW powered by a buck power converter. A schematic diagram of this DHB converter is shown in figure 2.

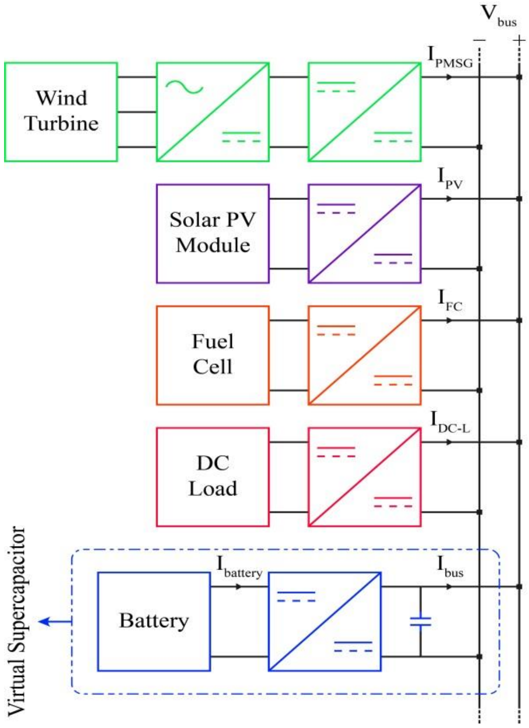

**Figure 1. Structure and configuration of DCMG.**

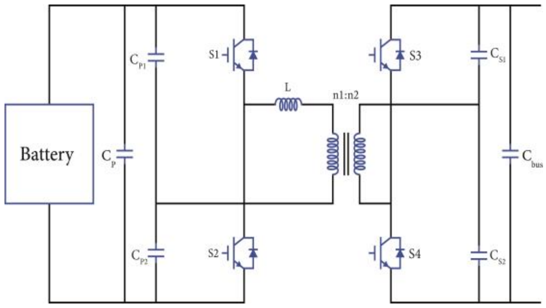

**Figure 2. DHB converter.**

## 3. Concept of VIE and Supercapacitor Modeling

Power generation using RESs causes problems such as significantly reducing inertia in the grid. This affects the performance and stability of the system. Hence, the VIE technique for DCMGs has been considered. Therefore, applying different inertia emulation methods can help improve the system stability. In a rotating machine, the energy stored in the rotor is defined as follows:

$$\mathbf{W_r} = \frac{1}{2}\mathbf{J}(\boldsymbol{\omega}_\mathbf{r}^\mathbf{m})^2 \tag{1}$$

*J* is the moment of inertia of the rotating machine, $\omega_r$ is the angular velocity of the rotor, and $W_r$ is the kinetic energy stored in the rotor of the machine. The equation of the energy stored in the capacitor is expressed as follows:

$$\mathbf{W_c} = \frac{1}{2}\mathbf{C}(\mathbf{v})^2 \tag{2}$$

where $W_c$ is the electrical energy stored in the capacitor, and *C* and *V* represent the capacitance and voltage of the capacitor, respectively. Therefore, the above relations can be assumed to be equivalent to each other, i.e. $W_r \equiv W_c$, and can be expressed as follows:

$$\frac{1}{2}\mathbf{J}(\boldsymbol{\omega}_\mathbf{r}^\mathbf{m})^2 \equiv \frac{1}{2}\mathbf{C_{dc}}(\mathbf{v_{bus}})^2 \tag{3}$$

Equation (3) shows that the capacitor has the same function as the machine rotor, and can be used instead of the rotor in order to control the inertial simulation in DCMG. Given that the capacitor voltage does not change rapidly, and using the same property, it can be stated that its inertia is similar to that of rotating generators, and acts as a source of kinetic energy storage in rotating machines. Therefore, it can be said that the equation governing the capacitor does not have the complexities of rotating machines by preserving important terms to emulate the inertia properties similar to the inertia of rotating machines. According to the above equations, a virtual inertia control strategy is implemented as follows:

$$\mathbf{I_C} = \mathbf{C_v}\frac{\mathbf{dv}}{\mathbf{dt}} + \mathbf{G_v}\mathbf{v} \tag{4}$$

where $C_v$ is the capacity of the virtual capacitor, $G_v$ is the capacity of the virtual conductor, *V* is the voltage of the capacitor, and $I_c$ is the virtual capacitor current.

## 4. Virtual Supercapacitor

The virtual supercapacitor unit consists of the ESS, DHB power converter, and a control mechanism. In this structure, the DHB converter is used as an interface between the battery pack and the DC bus. This converter was selected in the study design due to its high power density, electrical insulation, low device stress, low noise, inherent soft switching, and low cost. In the control block, the equation governing the exact model of the capacitor is placed. All values are listed in Table (1). The unit consists of a voltage controller, an inertia emulation unit, and a current control unit. In the voltage control unit, the amount of voltage deviation from the reference value enters the proportional-integral (PI) controller. The output of this unit is the voltage of the virtual supercapacitor, and after passing through the inertia emulation unit, which includes the mechanical equations of the capacitor, the supercapacitor current is determined. This current, which is the same as the battery reference current, enters the current control unit. The PI controller in this section determines the appropriate switching. The PI controller calculates an appropriate output based on the error. This controller is adjusted to prevent high fluctuations, and the system speed is in the desired range, and also resets the steady-state response to zero. By placing a first-order low-pass filter (LPF) in series in the virtual supercapacitor control unit, high-frequency noise can be prevented. A block diagram of this unit is shown in figure 3. The virtual supercapacitor unit can operate in different modes and suppress fluctuations by exchanging power and give DCMG stability. By considering the amount and direction of the power of this unit, different performance modes can be examined. The DCMG power balance equation is defined as follows.

$$\mathbf{P_{VSC}^{out}} = \mathbf{P^{load}} - \mathbf{P^{gen}} \tag{5}$$

$$\mathbf{P^{load}} = \mathbf{P_{DC-L}} \tag{6}$$

$$\mathbf{P^{gen}} = \mathbf{P_{PMSG}^{gen}} + \mathbf{P_{PV}^{gen}} + \mathbf{P_{FC}^{gen}} \tag{7}$$

$$\mathbf{P^{gen}} = \mathbf{P_{PMSG}^{gen}} + \mathbf{P_{PV}^{gen}} + \mathbf{P_{FC}^{gen}} \tag{8}$$

In which $P_{\mathrm{PMSG}}^{\mathrm{gen}}$, $P_{\mathrm{PV}}^{\mathrm{gen}}$, and $P_{\mathrm{FC}}^{\mathrm{gen}}$ are the output power of WT, PV, and FC, respectively, and $P_{\mathrm{DC-L}}$ is the power consumption of the DC load.

When the generation power in DCMG is greater than the demand, i.e. $P^{\mathrm{gen}} > P^{\mathrm{load}}$, the DC bus will be overvoltage. The virtual supercapacitor unit returns the DC bus voltage to its reference value by storing the extra power in the battery. In this case, the virtual supercapacitor unit is in the charge mode, and controls the DC bus voltage by receiving additional power. When the consumers demand more power than the production power, it will be $P^{\mathrm{gen}} < P^{\mathrm{load}}$. In the conditions, the DC bus has a voltage drop. The virtual supercapacitor unit compensates for the power shortage by injecting power through discharge and restores stability to DCMG. When the power balances between the supply and demand, $P_{\mathrm{VSC}}^{\mathrm{out}} = 0$. In this case, the DC bus voltage is set exactly to its reference value.

**Table 1. Parameters of virtual supercapacitor.**

| Part | Parameter | Symbol | Value |
|---|---|---|---|
| Virtual capacitor controller | Virtual capacitor | Cv | 0.002 |
| DHB converter | Virtual conductor | Gv | 0.5 |
| | Bridge capacitors | $C_{p1}, C_{p2}, C_{s1}, C_{s2}$ | 100 µF |
| | Filter capacitor | $C_p$ | 1.5 mF |
| | Filter capacitor | $C_{bus}$ | 1.5 mF |
| High frequency transformer | Power | --- | 7.5 KVA |
| | Auxiliary inductance | L | 4.5 µH |
| | Turns ratio | n | 96/400 |
| | Switching frequency | $f_s$ | 5 kHz |

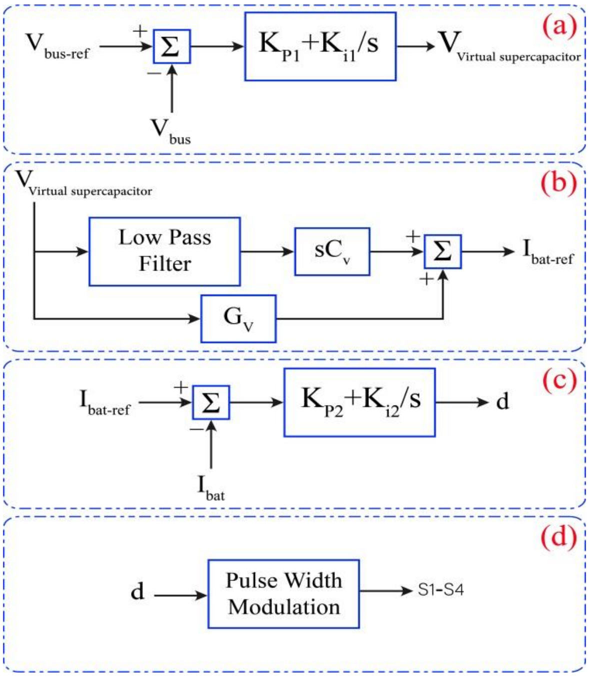

**Figure 3. Block diagrams of control: (a) Voltage controller, (b) Virtual capacitor controller, (c) Current controller, (d) Pulse width modulation.**

## 5. Simulation Results

The most important factor influencing the DC bus voltage is the power balance in DCMG. In this regard, during different scenarios, an attempt was made to examine the capabilities of the proposed scheme. Therefore, in DCMG, during the load change scenario, the ability of the proposed virtual supercapacitor unit to maintain the stability of DCMG through DC bus voltage control was investigated. Then the proposed scheme was tested on the resource change scenario and the generation capacity of WT and PV. DCMG simulation was performed in the MATLAB/Simulink software environment.

### 5.1 Virtual supercapacitor unit performance in load change

The PV, WT, and FC units deliver 6 kW, 4.5 kW, and 3 kW powers, respectively. In the first scenario, wind speed and solar radiation, and consequently, changes in the power of constant sources were considered. The DC load unit with a maximum input power of 15 kW was considered the DCMG consumers. In the first 0.4 s, the DC load demanded a 12 kW power, and our output power was 13.5 kW. Thus as shown in figure 4(a), the virtual supercapacitor unit adjusts the bus voltage to the reference value by storing additional power. As shown in figure 4(b), the battery current is negative, and the virtual supercapacitor unit is in the charge mode. At 0.4 s, a 1.5 kW load was added. The load reached 13.5 kW. In this case, the bus voltage dropped. Due to the support of the virtual supercapacitor unit and by emulation of the inertia in DCMG, the DC bus fluctuations were quickly prevented, and as shown in figure 4(a), the bus voltage was kept constant at the reference value. As shown in figure 4(b), the battery current was set to zero, indicating that the virtual supercapacitor unit had no power exchange with DCMG. At 0.8 s, a 1.5 kW load was added again. The DCMG load reached its maximum capacity. The bus voltage dropped again, which according to figure 4(a), was compensated by the energy stored in the virtual supercapacitor unit. According to figure 5(a), the current of the virtual supercapacitor was positive, and this unit was in the discharge mode. As seen in figure 5(a), at 1.2 s, by disconnecting the load 1.5 kW DC, the DC bus voltage increased, which was suppressed by the virtual supercapacitor unit. The battery current was set to zero, and in this case, the virtual capacitor super unit was in the floating mode. In the last period at 1.6 s, a 1.5 kW DC load would be disconnected. This unit will return to the charging mode. As shown in figures 4(a) and 5(a), the proposed scheme could meet this challenge well.

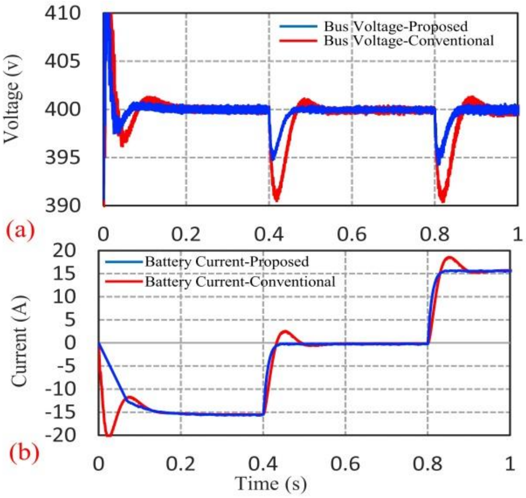

**Figure 4. Simulation results in the first second (a) DC bus voltage (b) Battery current.**

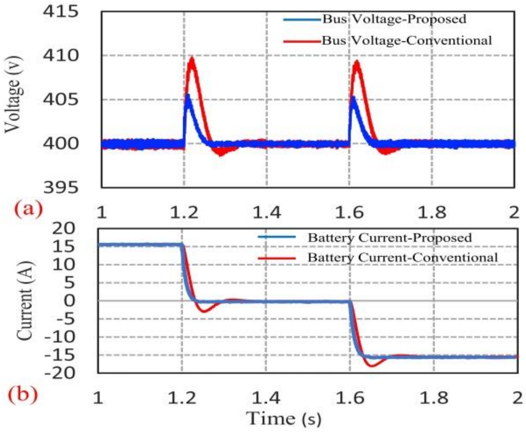

**Figure 5. Simulation results in the final second (a) DC bus voltage (b) Battery current.**

### 5.2 Virtual supercapacitor unit performance in source power change

In order to evaluate the performance of the proposed scheme, the second test scenario was performed under the PV and WT power change conditions. The DC load with a value of 13.5 kW was considered the DCMG consumer. The amount of DC load would remain constant until the end of the simulation. Also the amount of power output of FC was 3 kW, and would not change. At the beginning of the simulation, the amounts of production capacity and demand were equal. Therefore, as one can see in figure 6 (a), the bus voltage is at its reference value, and the virtual supercapacitor unit is in the floating mode according to figure 6 (b). In 0.4 s, the WT power decreased from 4.5 kW to 3.5 kW. As shown in figure 6(a), the bus voltage dropped. Due to the support of the virtual supercapacitor unit and by emulation inertia in DCMG, the DC bus fluctuations were quickly prevented. Therefore, the virtual supercapacitor unit returned the voltage to the reference value. In this case, the battery current would be positive. Therefore, this unit would be in the discharge mode. According to figure 6(c), in 0.8 s, the power of PV decreased from 6 kW to 5 kW. In this case, the bus voltage dropped again, and the virtual supercapacitor unit was responsible for supplying the required power. As shown in figure 6(b), the battery current would increase again in order to provide more power to DCMG. According to figure 7(c), the WT power returned to its initial value in 1.2 s. The DC bus voltage increased, and the virtual supercapacitor unit stored an extra power in order to prevent overvoltage of the bus. The battery current also decreased. In the last period, the power of the PV power returned to its initial value. According to figure 7(a), the bus voltage increased again, and the virtual supercapacitor unit returned the bus voltage to the reference value by storing an additional power. As one can see in figure 7(b), the battery current would also be set to zero so the virtual supercapacitor unit had no power exchange with DCMG and would return to the floating state. As shown in figures 6(a) and 7(a), the proposed scheme could meet this challenge well, and keep the DC bus voltage in the desired range. In this case, the voltage deviation from its reference value was only about 2 V.

## 6. Conclusions

In this paper, by studying the methods of inertial emulation in DCMGs, a virtual supercapacitor strategy to reduce low inertia problems was proposed. Due to the high efficiency, electrical insulation, inherent soft switching, and the requirement for a smaller filter, the DHB converter was used. The simulation results obtained showed that the proposed control strategy could suppress the DC bus voltage variations. In addition, the DC bus voltage deviation from the reference value at the time of fault was decreased by about 5 V compared to the conventional scheme. In order to optimize the battery performance, it was desirable to consider the state-of-charge (SOC) during the operation. Therefore, the battery life was improved by decreasing the charge/discharge rate. Thus the distributed converters must achieve a power balance and SOC, while stabilizing the DC bus voltage. Future works may focus on designing faster controllers and SOC.

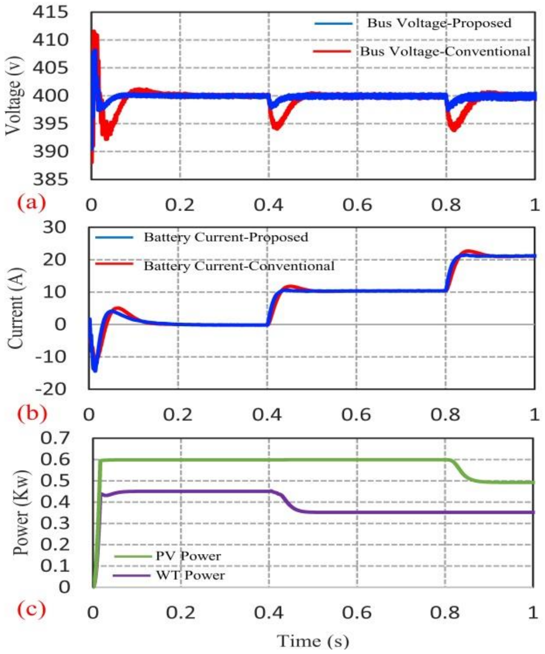

**Figure 6. Simulation results in the first second (a) DC bus voltage (b) Battery current (c) Generated power.**

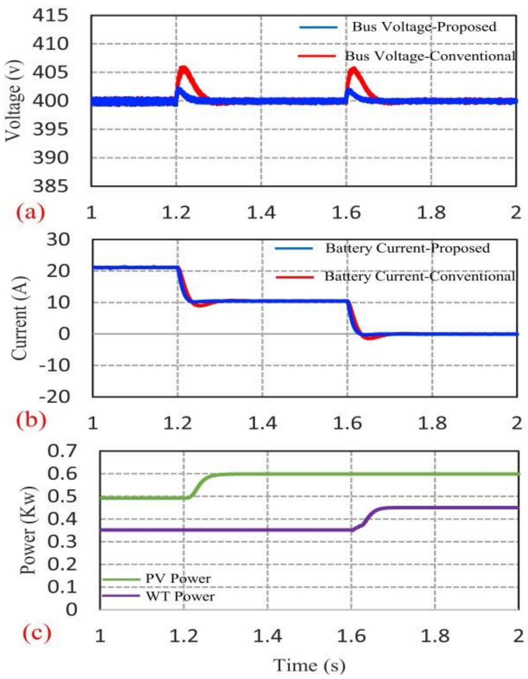

**Figure 7. Simulation results in the first second (a) DC bus voltage (b) Battery current (c) Generated power.**

## 7. Acknowledgment

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## 8. References

[1] Dreidy, M., Mokhlis, H., and Mekhilef, S. (2017). Inertia response and frequency control techniques for renewable energy sources: A review. Renewable and sustainable energy reviews, Vol. 69, pp. 144-155.

[2] Yi, Z., Zhao, X., Shi, D., Duan, J., Xiang, Y., and Wang, Z. (2019). Accurate power sharing and synthetic inertia control for dc building micro-grids with guaranteed performance. IEEE Access, Vol. 7, pp. 63698-63708.

[3] Wu, W., Chen, Y., Luo, A., Zhou, L., Zhou, X., Yang, L., ... and Guerrero, J.M. (2016). A virtual inertia control strategy for DC micro-grids analogized with virtual synchronous machines. IEEE Transactions on Industrial Electronics, Vol. 64, No 7, pp. 6005-6016.

[4] Samanta, S., Mishra, J.P., and Roy, B.K. (2018). Virtual DC machine: an inertia emulation and control technique for a bidirectional DC–DC converter in a DC micro-grid. IET Electric Power Applications, Vol. 12, No 6, pp. 874-884.

[5] Pishbahar, H., Moradi CheshmehBeigi, H., Piri Yengijeh, N., and Bagheri, Shokoofeh (2021). Inertia emulation with incorporating the concept of virtual compounded DC machine and bidirectional DC–DC converter for DC micro-grid in islanded mode. IET Renewable Power Generation, Vol. 15, pp. 1812-1825.

[6] Samanta, S., Mishra, J.P., and Roy, B.K. (2019). Implementation of a virtual inertia control for inertia enhancement of a dc micro-grid under both grid connected and isolated operation. Computers and Electrical Engineering, Vol. 76, pp. 283-298.

[7] Zhu, X., Meng, F., Xie, Z., and Yue, Y. (2019). An inertia and damping control method of DC–DC converter in DC micro-grids. IEEE Transactions on Energy Conversion, Vol. 35, No 2, pp. 799-807.

[8] Zhu, X., Cai, J., Yan, Q., Chen, J., and Wang, X. (2015). Virtual inertia control of wind-battery-based islanded DC. Int. Conf. Renewable power Generation (RPG). Beijing, China.

[9] Zhi, N., Ding, K., Du, L., and Zhang, H. (2020). An SOC-based virtual DC machine control for distributed storage systems in DC micro-grids. IEEE Transactions on Energy Conversion, Vol. 35, No 3, pp. 1411-1420.

[10] Jami, M., Shafiee, Q., Gholami, M., and Bevrani, H. (2020). Control of a super-capacitor energy storage system to mimic inertia and transient response improvement of a direct current micro-grid. Journal of Energy Storage, Vol. 32, pp. 101788.

[11] Molina, M.G. (2017). Energy storage and power electronics technologies: A strong combination to empower the transformation to the smart grid. Proceedings of the IEEE, Vol. 105, No 11, pp. 2191-2219.

[12] Pan, X., Li, H., Liu, Y., Zhao, T., Ju, C., and Rathore, A.K. (2019). An overview and comprehensive comparative evaluation of current-fed-isolated-bidirectional DC/DC converter. IEEE Transactions on Power Electronics, vol. 35, No 3, p. 2737-2763.