Performance Analysis of a DC Microgrid Integrated Dynamic Voltage Restorer with Model Predictive Control Strategy

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Abstract - *The dynamic voltage restorer is a device which is used to compensate grid voltage sag and swell which is occurs in the power system. Dynamic voltage restorer is controlled by various control strategy. This paper focused on DVR which is supported by a DC microgrid and controlled by a model predictive control strategy. A DC microgrid contains PV array and hybrid energy storage consisting of lithium-ion battery and a super capacitor. A conventional DVR which is supported by a pure energy storage unit is less efficient compared with this proposed system. The DC microgrid will prolong the operating time of DVR because PV array supply the DVR and also charge the HESS occasionally. In order to analyse the performance of a DC microgrid supported DVR system with MPC controlling method simulation study is included with sag and swell scenarios.*

Key Words: Dynamic voltage restorer (DVR), Model predictive control (MPC), DC microgrid, Hybrid energy storage system (HESS), PV array.

1. INTRODUCTION

During last some years, the DC microgrids have take a researchers attention. In DC microgrids, it consist of renewable energy sources i.e., PV array, wind turbines, Batteries, super capacitors [1]. Generally the DC microgrid works in two basic modes first one is isolated mode and second one is grid connected mode. In this a grid interfacing power quality compensator shunt and series voltage inverters are connected to the microgrid to improve the power quality of the line currents in the system [2]. Generally the dynamic voltage restorer shows different topologies [3]. There are many control strategies of DVR for the proper working of the dynamic voltage restorer [4][5][7].

The conventional DVR which supported by a dc link capacitor[6] has some disadvantages which is overcome by the proposed system. A DVR is also used with a renewable energy sources like PV array system. In this system PV array generates DC energy which is used as a DC storage unit [8][12][13][15].But due to discontinuity of a PV array power generation it may have some disadvantages so this also overcome by the proposed system. The dynamic voltage restorer is also used with battery energy storage system only or supported with supercapacitor only [11][14][17] as a storage devices which after connected with the VSI system. DVR is worked efficiently when it works with the better, fast and effective control system which is explained[10]. In a proposed system DVR is controlled with the help of model predictive control strategy. This control scheme is better than the others. This controller is more advanced than the other controllers. A model predictive control is used for gate pulses generation purpose to control voltage source inverter for the UPS applications [9] with output LC filter.

In a proposed system integrated DC microgrid is used to supply DC energy for DVR working. A DC microgrid consist of a PV array, hybrid energy storage unit which consist of lithium ion battery and super capacitor system. DVR controlled by MPC control method. A PV array and HESS both are parallel connected to each other and it supplies the DC power to the DVR system for sag/swell mitigation purpose[16]. This paper presents a performance analysis of DC microgrid integrated DVR with model predictive control. Compared to the conventional system this proposed system extended operating time of DVR because renewable energy source and hybrid energy storage unit is used combinely. The performance of the proposed system is validated through the MATLAB 2016a simulation results.

2. PROPOSED DC MICROGRID INTEGRATED DVR SYSTEM

The system architecture of the DC microgrid integrated DVR is shown in Fig. 1. For the DVR side, there is an injection transformer, a VSI and a LC filter with a damping resistor. $v_{s,abc}$, $i_{s,abc}$, $v_{L,abc}$ and $i_{L,abc}$ denote the grid voltage, grid current, load voltage and load current respectively. $v_{f,abc}$, $i_{f,abc}$, $v_{dvr,abc}$ and $i_{dvr,abc}$ are the input voltage and input current, output voltage and output current of the filter. $L_{f,abc}$, $C_{f,abc}$ and $R_{f,abc}$ denote the inductors, capacitors and damping resistors in the filter with the values of L, C, R respectively. Also, The VSI has six switches S_i and S_i' (i=1,2 and 3) controlled by model predictive control technique q_i and q_i'. For the DC microgrid, v_{bus} , i_{bus}, C_{bus} and R_{bus} represent the DC bus voltage, current, capacitor and load respectively. The PV array is connected to the DC bus via a boost converter with the maximum power point tracking (MPPT) algorithm, where v_{pv} and i_{pv} are the voltage and current of PV array, and L_{pv}, S_{pv} and D are the inductor, IGBT switch and diode respectively. The lithium-ion battery and super capacitor are assigned with the bidirectional buck/boost converter to conduct the charge/discharging operation. The corresponding voltage, current, switches and capacitors are $v_{bat}, i_{bat}, v_{sc}, i_{sc}, S_{bat\,1}, S_{bat\,2}, S_{sc\,1}, S_{sc\,2}, C_{bat}$ and C_{sc}.

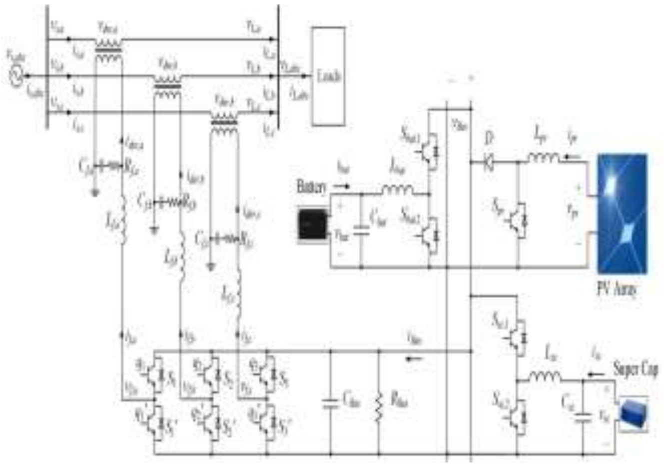


Fig -1: Proposed DC microgrid integrated DVR system

Model Predictive Control for DVR

The switches states of the VSI are determined based on the corresponding signals as follows:

$$q_i = \begin{cases} 1, if\ S_i\ on\ and\ S_i' off \\ 0, if S_i\ off\ and\ S_i' on \end{cases} \quad \ldots\ldots (1)$$

Hence, $v_{f,abc}$ can be obtained

$$v_{f,abc} = v_{DC}[q_1 \quad q_2 \quad q_3]^T \quad \ldots\ldots (2)$$

$v_{f,abc}$ is expressed as $v_{f,\alpha\beta}$ after the $\alpha\beta$-transformation as follows:

$$v_{f,\alpha\beta} = v_{DC}\begin{bmatrix} 1 & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad \ldots\ldots (3)$$

Similarly, $v_{dvr,abc}$, $i_{f,abc}$ and $i_{dvr,abc}$ are expressed as $v_{dvr,\alpha\beta}$, $i_{f,\alpha\beta}$ and $i_{dvr,\alpha\beta}$ with the $\alpha\beta$-transformation. Hence, the equations describing the *LC* filter are shown as follows:

$$L\frac{di_{f,\alpha\beta}}{dt} = v_{f,\alpha\beta} - v_{dvr,\alpha\beta} \quad \ldots\ldots (4)$$

$$C\frac{d\left(v_{dvr,\alpha\beta} - R\left(i_{f,\alpha\beta} - i_{dvr,\alpha\beta}\right)\right)}{dt} = i_{f,\alpha\beta} - i_{dvr,\alpha\beta} \quad \ldots\ldots (5)$$

Where $i_{dvr,\alpha\beta}$ as the constant value with a high sampling frequency. By substituting (4) into (5) and, it can be obtained as follows:

$$\frac{dv_{dvr,\alpha\beta}}{dt} = \frac{R}{L}\left(v_{f,\alpha\beta} - v_{dvr,\alpha\beta}\right) + \frac{1}{C}\left(i_{f,\alpha\beta} - i_{dvr,\alpha\beta}\right) \quad \ldots\ldots (6)$$

The discretization of (6) can be obtained using forward-Euler method with a preset time step of *TS*, as shown below:

$$v_{dvr,\alpha\beta}(k+1) = \left(1 - \frac{T_s R}{L}\right)v_{dvr,\alpha\beta}(k) + \frac{T_s R}{L}v_{f,\alpha\beta}(k) + \frac{T_s}{C}\left(i_{f,\alpha\beta}(k) - i_{dvr,\alpha\beta}(k)\right) \quad \ldots\ldots (7)$$

The reference of $v_{dvr,\alpha\beta}$ is defined as $v_{dvr,\alpha\beta}{}^*$ which is expressed as follows:

$$v_{dvr,\alpha\beta}{}^* = \begin{bmatrix} 1 & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{bmatrix}\begin{bmatrix} \sqrt{2}(v_{L,rms}{}^* \sin\omega t - v_{s,a} \\ \sqrt{2}(v_{L,rms}{}^* \sin(\omega t - \frac{2}{3}\pi) - v_{s,b} \\ \sqrt{2}(v_{L,rms}{}^* \sin(\omega t + \frac{2}{3}\pi) - v_{s,c} \end{bmatrix} \quad \ldots\ldots (8)$$

where $v_{L,rms}{}^*$ is the RMS value of nominal amplitude of $v_{L,abc}{}^*$ and the synchronization angle ωt can be obtained using $v_{S,abc}{}^*$ and phase-locked loop. A cost function is defined in (9), and it determines the optimal control action which can minimize (9).

$$J = \left|v_{dvr,\alpha\beta}{}^* - v_{dvr,\alpha\beta}\right| \quad \ldots\ldots (9)$$

There are eight possible values of the vector $[q_1 \quad q_2 \quad q_3]^T$ based (1). By setting prediction horizon and control horizon set as 1, the number of the predicted values of $v_{dvr,\alpha\beta}$ is also eight, so that the enumeration of (9) can be conducted to determine the optimal value of $[q_1 \quad q_2 \quad q_3]^T$ and the computational burden is low considering the limited number of enumeration.

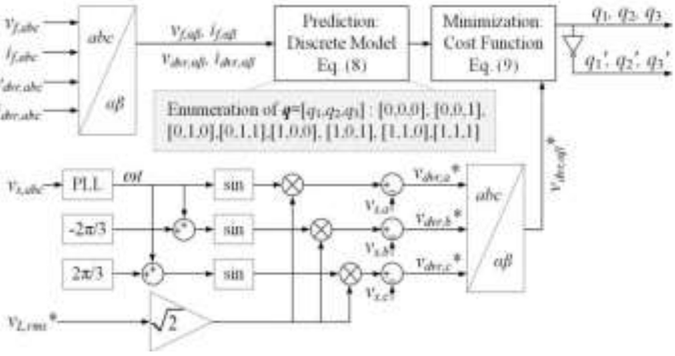


Fig -2: MPC based control for DVR

3. SIMULATION MODEL AND RESULTS

A series of study cases are simulated in the MATLAB/Simulink to validate the performance of the proposed DC microgrid integrated DVR system. Two simulation study cases including voltage sag scenario and voltage swell scenario. The setting parameters of the proposed system are listed in Table I, including the setting of grid, DVR, load, DC microgrid, battery and supercapacitor. Simulation setting parameters for the proposed system is as follows:

Table -1: Simulation model parameters

	Parameters	Values
Grid	Nominal phase voltage *vs,abc*	50V
	Frequency	50Hz
DVR	VSI Switching frequency	100kHz
	VSI Filter inductor	6.3mH
	VSI Filter capacitor	200µF
	VSI Filter damping resistor	10Ω
	Transformer turns ratios	1
Load	Nominal phase voltage	50V
DC Microgrid	DC bus capacitor CBus	4700µF
	DC bus load RBus	50 Ω
	DC bus voltage vBus	80V
Battery	Nominal voltage vbat	50V
	Initial SOC	40%
Supercapacitor	Nominal voltage vsc	60V
	Initial SOC	100%

In a fig.3 shows a simulation model for the DC microgrid integrated DVR with model predictive control. Here three phase voltage source is used which is supplied 50 V to the load of 50 V. In a MATLAB model Fault block is inserted for the sag/swell occurrence purpose. In this system DC microgrid contains PV array which is shown in fig.4 and lithium ion battery of 50 V with initial state of charge 40% and it is parallel to the super capacitor of 60V with initial state of charge 100%. the battery and super capacitor model in which buck/boost converter for the charging and discharging purpose. Vbattery=50V and Initial SOC=40%, Vsupercapacitor=60V and Initial SOC=100% for this system.

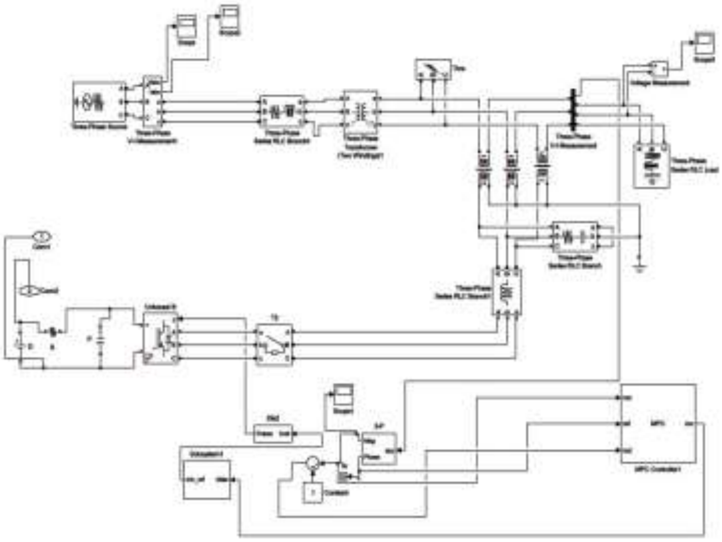


Fig -3: Simulation model for DC microgrid integrated DVR with MPC block

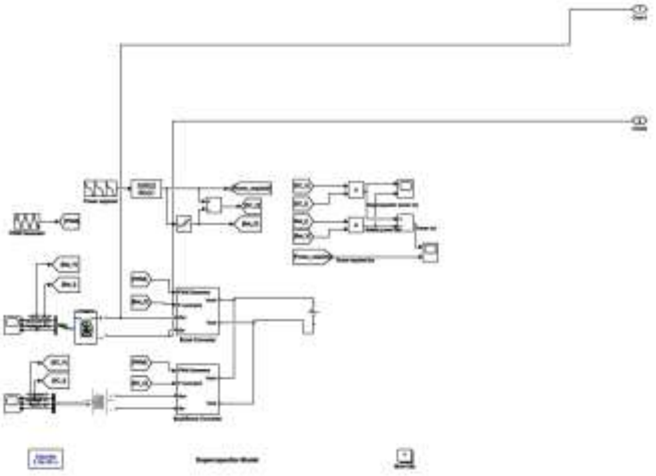


Fig -4: Simulation model for battery and super capacitor model

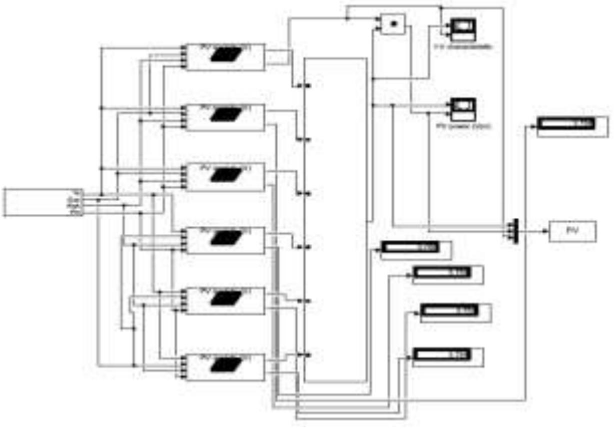


Fig -5: Simulation model for Simulation model for PV subsystem

A study cases are simulated in the MATLAB/Simulink to analyse the performance of the proposed DC microgrid integrated DVR system, and the corresponding simulation results are discussed here. Two simulation cases study includes voltage sag scenario and voltage swell scenario.

A. Voltage Sag Scenario

Fig.6 and 7 shows the simulation results of source voltage with sag and compensated load voltage. In voltage sag scenario it can be seen that the source voltage have a sudden sag from the nominal phase voltage value 50V to 30V when t=0.1 s as shown in fig. powered by the DC microgrid , the MPC controlled DVR can inject the compensation voltage. Hence, load voltage can be maintained at a nominal phase value 50Vduring the voltage sag period 0.1 sec to 0.26 sec.

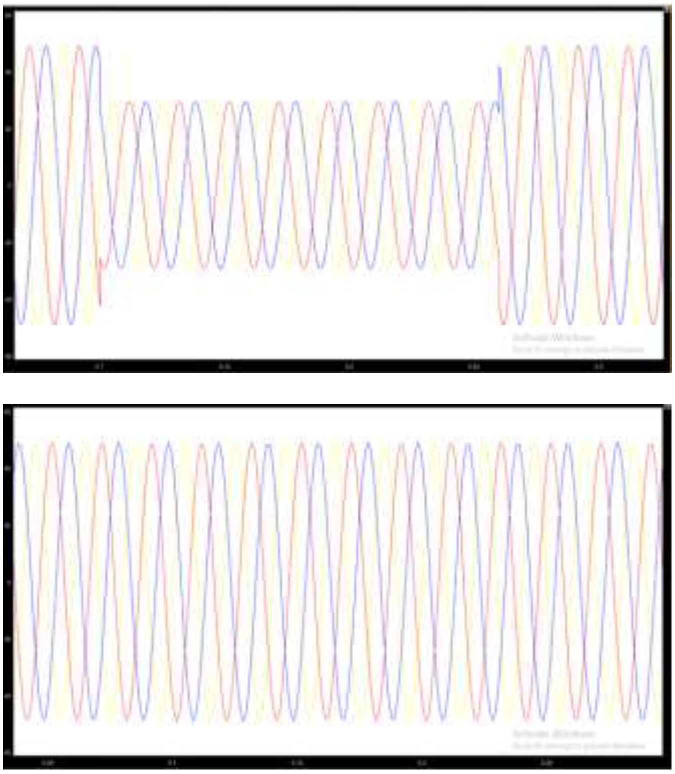
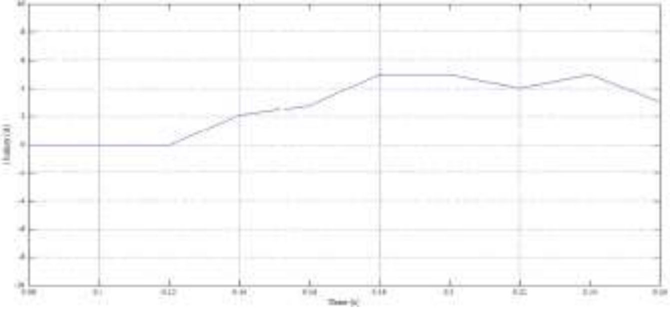


Fig -6: Simulation results of source voltage and load voltage in sag scenario



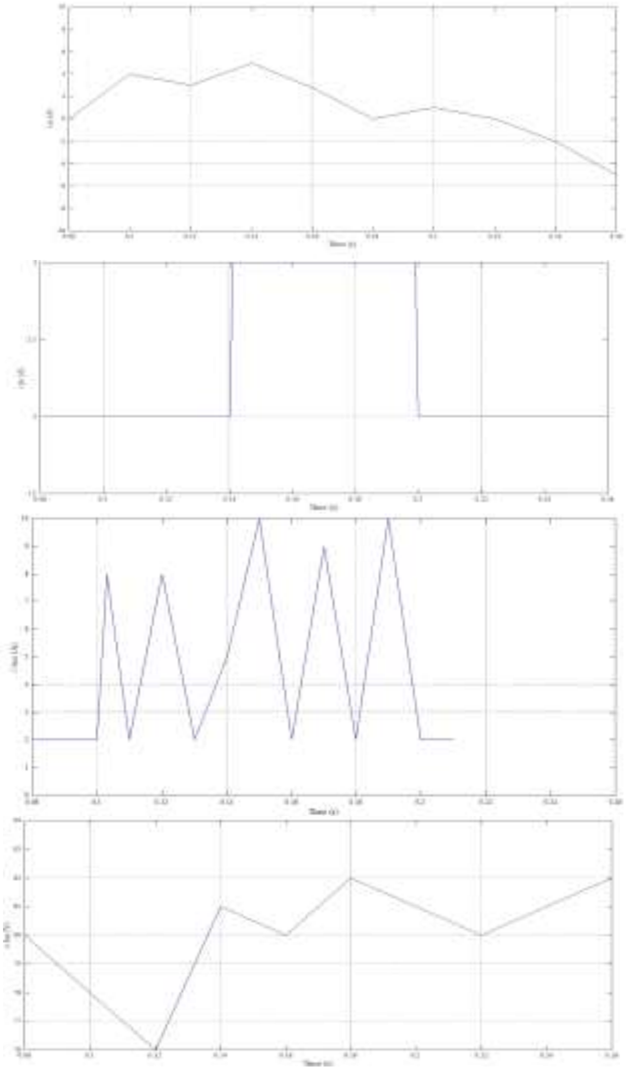


Fig -7: Simulation results of a DC microgrid in sag scenario

Fig.7 shows the waveforms of the DC microgrid during the voltage sag slot. It can be observed that the battery is charged by the PV array via DC bus at a normal condition when sag is not occurs. When sag happens at t= 0.1 sec I bus varies dramatically due to the voltage sag compensation. Hence battery and super capacitor are discharged at sag condition at t=0.1 to 0.6 s to maintain DC bus voltage constant upto 75V to 85V which is nearly equals to 80V. 5 to 10% tolerance is negligible.

B. Voltage Swell Scenario

Fig.8 and 9 shows the simulation results, of the proposed system in voltage swell scenario. Fig.8 shows that the source voltage have a sudden swell from the nominal phase vase value 50V to 70V when t=0.1s. Accordingly, the compensation voltage is inject by the DC microgrid powered DVR with MPC control, so that load voltage is regulated at the nominal phase value 50V during the whole voltage swell slot from t=0.1 sec to 0.26 sec.

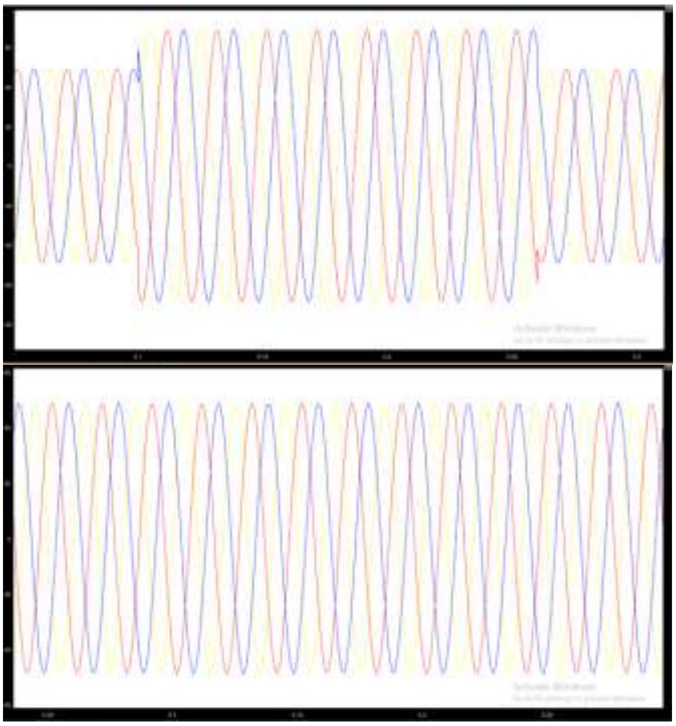
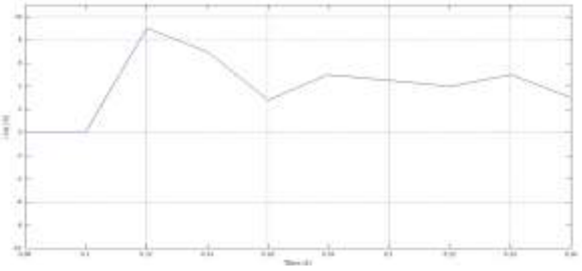
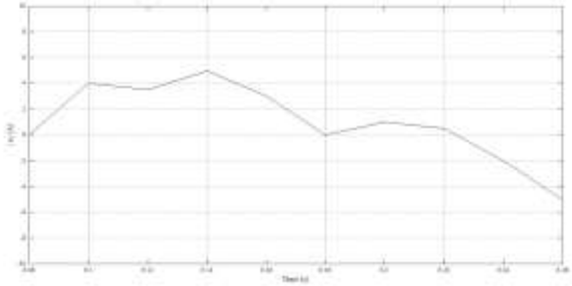
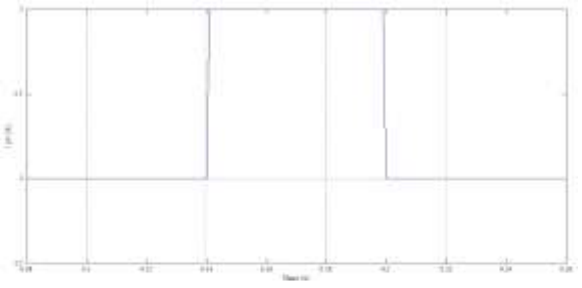


Fig -8: Simulation results of source voltage and load voltage in swell scenario







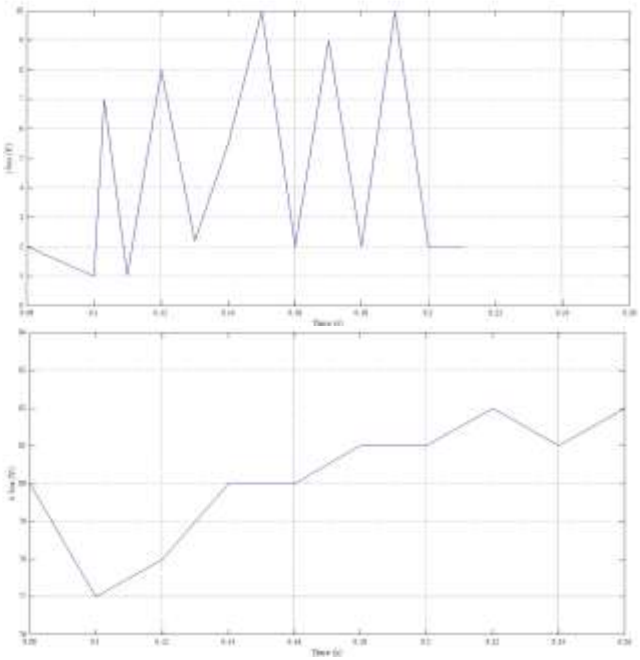


Fig -9: Simulation results of DC microgrid in swell scenario

Fig.9 shows the simulation results of a DC microgrid when swell occurs in the grid voltage. It can be observed that the battery is charged by the PV array via DC bus at a normal condition when swell is not occurs. When swell happens at t= 0.1 sec I bus varies dramatically due to the voltage swell compensation. Hence battery and super capacitor are discharged at swell condition at t=0.1 to 0.6 s to maintain DC bus voltage constant upto 77V to 82V which is nearly equals to 80V. 5% to 10% difference in bus voltage is to be considered.

4. CONCLUSION

From the simulation results it is conclude that at the both sag and swell condition it is important to maintain the DC bus voltage at the constant bus voltage upto 80V. For that purpose we are using the DC grid of PV array and battery and super capacitor. Hence proposed DVR system is able to achieve compensation of sag/swell with the maintaining stable DC bus voltage.

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