Voltage Support Scheme for Low Voltage Distribution Grids Under Voltage Sags

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***Abstract*—A grid-connected power electronics based distributed generator can act as an active element by providing support to the grid under various disturbances. In this paper, a voltage support scheme dedicated for distributed generators installed in the low voltage distribution network is proposed. The voltage support considers the resistive characteristics of the distribution line grid impedance in order to maximize its effectiveness. Therefore, the optimal active and reactive current references are estimated based on the resistance to reactance ratio (*R/X*). Moreover, a droop curve is suggested such that the intensity of voltage support will be defined according to the voltage drop conditions. The proposed voltage support concept is applied on a photovoltaic system to validate its operation. The effectiveness of the proposal is confirmed by means of simulations in a realistic low voltage distribution network.**

***Index Terms*—fault ride through operation, low voltage distribution grid, photovoltaics, voltage support scheme.**

I. Introduction

Power electronics based distributed generators (DGs) are increasing dramatically in the distribution network due to environmental concerns for reduction of CO2 emissions and their cost-effectiveness. The stability of the grid is threatened during voltage disturbances and the system stability will be more vulnerable as the penetration level of DGs will rise. For this reason, Fault Ride Through (FRT) capability is demanded by grid codes [1]. Hence, there is a great potential to identify new control concepts that can maximize the impact of the voltage support in distribution networks by exploiting the unique characteristics of such networks.

Voltage support by DGs is feasible due to the flexible and fast capabilities of power electronics converters to control the output currents. Although, advanced reference generation schemes have been studied extensively in the literature for voltage support, these concepts are mainly suitable for transmission grids [2]–[5]. The operation of these schemes is based on the extraction of the positive and negative sequence voltages which are fed into advanced current controllers working on the positive and negative rotating frames [6]–[9]. However, it should be noted that most of the studies consider mainly inductive grids: this is applicable only in transmission systems [2]–[7], [10], [11]. Hence, only reactive power is used to support the voltage during both balanced and unbalanced voltage drops.

A few works have proposed voltage support schemes for low voltage grids [12]–[15]. The resistive nature of the cables in the distribution grid is the key element that distinguish it from the transmission network and further investigation is required. In [14], a current reference generator is proposed based on the grid impedance. An optimization algorithm is proposed in [13] to maximize the voltage support in any *X/R* grid impedance ratio by maximizing the positive sequence voltage [13]. The authors extended the work for unbalanced voltage drops to minimize the negative sequence voltage, or by maximizing the difference between positive and negative sequence [12]. The authors in [12], [13] proposed that the converter should inject its rated current regardless of the voltage drop percentage. However, if this approach is applied in an actual distribution network, intense oscillations can occur due to the large discontinuities of the voltage support scheme.

Hence, the main contribution of this paper is the design of a tailor-made voltage support scheme for distribution grids where the resistive characteristics of distribution lines are properly considered and the support intensity depends on the level of voltage drop. It should be highlighted that a constant DC source is assumed in most of the studies [8], [9], [12]–[15], which simplify the controller and ignore the dynamics of the primary energy resource. In this work, a detailed model for a photovoltaic system is developed for primary energy resource to allow a more realistic study. Further, a corresponding DC-link controller and a Maximum Power Point Tracking (MPPT) algorithm is developed for coordinating the operation of the primary energy resource and to evaluate the response of each controller. In the proposed scheme, the Droop control approach is inherited from the transmission grid regulations in order to adjust the support intensity according to the voltage drop and thus, to minimize the discontinuities of the FRT operation. The converter current ratings are taken into account as well in order to ensure that the voltage support is provided without risking the integrity of the converter. Finally, the effectiveness of the proposed voltage support scheme is investigated in a realistic distribution system where it is demonstrated that the proposed scheme can contribute for enhancing the voltage stability of distribution grids.

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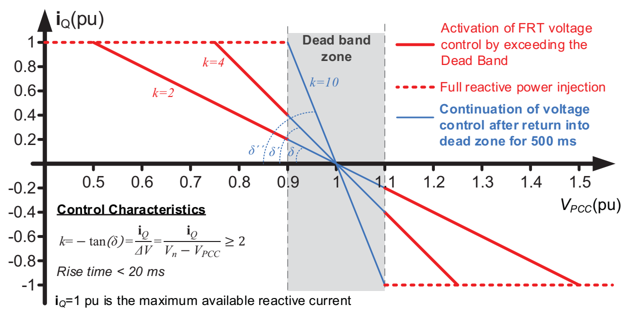

Figure 1. Reactive power support requirement by DGs under voltage disturbances according to the grid codes.

The paper is organized as follows: The proposed voltage support scheme is introduced in Section II. The implementation of the scheme on a photovoltaic system is described in Section III. The evaluation of the proposed scheme in a realistic distribution grid is presented in Section IV. Finally, Section V concludes the paper.

II. Voltage Support Scheme

This section describes the existing practices for FRT operation of DGs installed in distribution grids. Then, a voltage support scheme is proposed to cope with the limitations of the current concepts.

A. Disconnection of DG

Although, an FRT requirement for DGs that are connected to the transmission network does exist, this is not the case in distribution grids, and especially in low-voltage feeders. In most countries, small scale DGs installed in low voltage feeders are disconnected during intense voltage or frequency disturbances. The disconnection of DGs is introduced by the utilities mainly to avoid islanding and to protect the converter from over-current. However, as the penetration of residential DGs in the distribution feeders is increasing, this approach will not be effective and the stability of the grid will be threatened with potential domino effects that can lead to blackout.

B. Reactive Power Support

Reactive power support is introduced by some countries, such as Germany, Italy and Japan [1], to enable the provision of FRT capability from the residential DGs in the distribution system. This approach is mainly adopted from the transmission grid codes. According to the grid codes, if the voltage exceeds a dead-band zone, defined by the system operator, the DG should ensure its synchronization with the grid, remain connected and provide reactive power support as illustrated in Fig. 1. It should be highlighted that $\mathbf{i}_P$ and $\mathbf{i}_Q$ are defined as the currents that are in-line and 90^o lag with the voltage vector respectively. According to the grid codes the reactive current that should be injected is defined according to the voltage deviation as,

$$\mathbf{i}_Q = k(V_n - V_{pcc}) = k\Delta V \tag{1}$$

where V_n and V_{PCC} are the magnitude of the nominal voltage and of the voltage at the Point of Common Coupling (PCC) respectively. The parameter k is the droop constant which determines the intensity of the voltage support and as defined by grid codes should be equal or greater than 2. Since the regulations require reactive current provision, the active current ($\mathbf{i}_P$) should also be re-adjusted accordingly in order to ensure that the rated current (I_n) of the converter will not be violated. In case where the converter ratings are violated, the active current is defined as,

$$\mathbf{i}_P = \sqrt{I_n^2 - \mathbf{i}_Q^2} \tag{2}$$

C. Proposed Voltage Support Scheme

It should be highlighted here that the existing reactive power support scheme (as presented in Section II.B) is designed for transmission systems, where the resistance of the lines can be neglected since *X/R* ratios are usually high. The resistive nature of the lines in the distribution grid can impose significant differences in the voltage support concept. More specifically, the decoupled control approach for voltage and frequency by injecting reactive and active power respectively is not valid in a distribution network due to the resistive characteristics of distribution lines. Thus, for supporting the voltage during disturbances, delivery of both active and reactive power is required. This concept is presented in [13], however the main idea is also discussed here. The general structure of a DG connected to the grid through a Grid Side Converter (GSC) is shown in Fig. 2. The three-phase converter injects the power generated by the primary source to the grid through the grid impedance. Considering this structure, the voltage at the PCC can be written as,

$$\mathbf{v}_{PCC} = \mathbf{v}_g + \mathbf{i}R + \mathbf{i}X \tag{3}$$

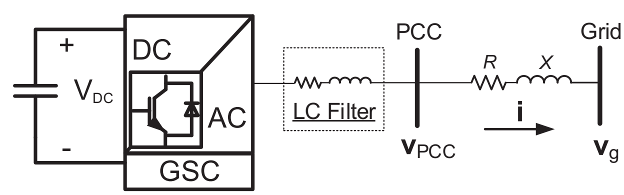

Figure 2. General structure of a DG connected to the grid.

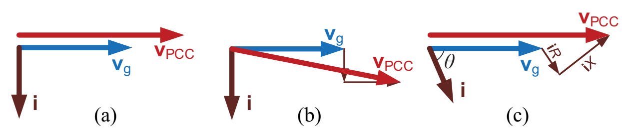

Figure 3. Vector diagrams: (a) Transmission network only reactive power, (b) Distribution network only reactive power, (c) Distribution network proposed voltage support scheme.

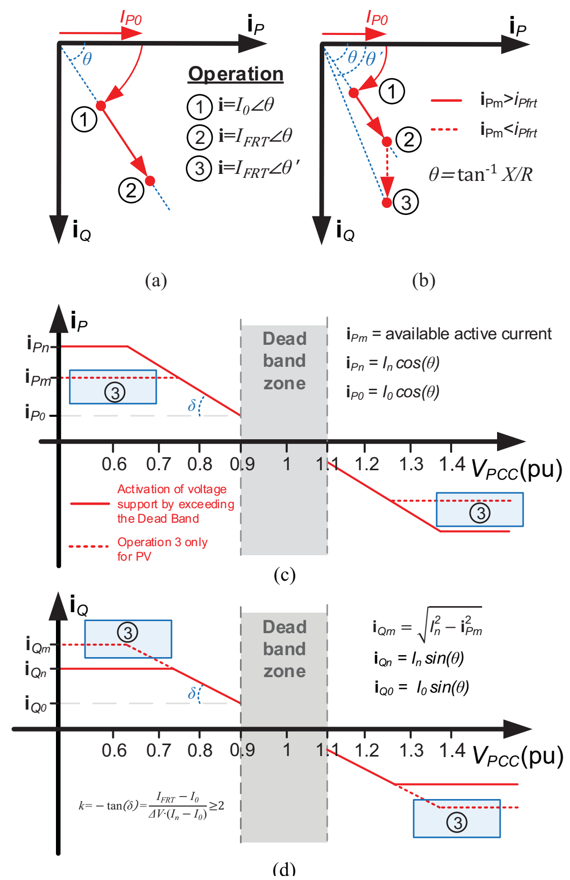

Figure 4. Description of the proposed voltage support strategy: (a) Active and reactive current in general form. (b) Active and reactive current special case for photovoltaic system, (c) Active current requirements according to the proposed voltage support scheme, (d) Reactive current requirements according to the proposed voltage support scheme.

where $\mathbf{v}_g = \left[v_{g_d}\, v_{g_q}\right]^T$ is the grid voltage vector, $\mathbf{v}_{PCC} = \left[v_{PCC_d}\, v_{PCC_q}\right]^T$ is the PCC voltage vector, $\mathbf{i} = \left[i_d\, i_q\right]^T$ is the current injection vector, R is the grid resistance and X is the grid reactance. Considering the voltage support scheme at the transmission grid where R is small compared to X, the term $\mathbf{i}R$ can be assumed to be zero. Hence, the maximum voltage support at the PCC is obtained when the vector $\mathbf{v}_g$ is aligned with the vector $\mathbf{i}X$ as is shown in Fig. 3a. In the case of the distribution network, the X/R ratio is considerably lower, hence the grid resistance cannot be neglected. If the aforementioned approach is used, it is clear that the voltage at the PCC is not the maximum one as illustrated in Fig. 3b. Therefore, the idea of this paper is to inject a current that maximizes the voltage at the PCC when both X and R are considered. A visualization of this concept is shown in Fig. 3c in which both terms ($\mathbf{i}R$ and $\mathbf{i}X$) contribute to the voltage support by injecting a current with the optimum angle. By solving (3) to identify the current vector that maximizes the voltage at the PCC, it can be demonstrated that for ensuring a maximum voltage support, a phase angle (θ) is required by the injected current according to the X/R ratio as,

$$\mathbf{i}_{FRT} = I_{FRT}\angle\theta \tag{4}$$

where $\mathbf{i}_{FRT} = \left[i_{P_{frt}}\, i_{Q_{frt}}\right]^T$ is the voltage support current vector, I_{FRT} is the voltage support current magnitude and $\theta = tan^{-1}(X/R)$.

A detailed description of the proposed voltage support scheme can be provided with the help of Fig. 4. Initially the DG operates with active current I_{P_0}. If it is assumed that a sudden voltage drop is applied and the voltage sag signal is enabled, the operation will shift from the initial condition to operational point 1 in which the current is $I_{P_0}\angle\theta$. Thereafter, a droop control approach as the one with the reactive power support scheme of [10] is applied such that the intensity of the support current is altered according to the voltage drop intensity. This is illustrated in the area from operational point 1 to operational point 2 of Fig. 4a where the FRT current is defined as $I_{FRT}\angle\theta$. It should be noted that the operational point 2 is limited by the rated current (I_n) of the converter in order to avoid the tripping of over-current protection. The droop constant (k) is defined by,

$$k = \frac{I_{FRT} - I_0}{\Delta V\left(I_n - I_0\right)} \tag{5}$$

One can notice that by using the proposed strategy in a photovoltaic system, the active current demanded ($i_{P_{frt}}$) during the voltage drop can be higher than the available active current ($\mathbf{i}_{Pm}$). Hence, in this case, the operation should be moved to operational point 3 as shown in Fig. 4b in which the active current is limited by the available active power and the reactive current is increased according to the intensity of the voltage drop. Although the support is not optimum anymore since the FRT currents have different angle than the proposed one, the benefits to the voltage support arise from the increase of the magnitude of the current. The pseudocode that describes the transition from operation point 2 to 3 is provided below.

TASK: Voltage Support Operation Selection

if $i_{Pm} > I_{FRT}cos(\theta)$ **then**
  $\mathbf{i} = I_{FRT}\angle\theta$ ▷ Operation 2
else
  $i_{P_{frt}} = \mathbf{i}_{Pm}$ ▷ Operation 3
  $i_{Q_{frt}} = k\Delta V$
  $\mathbf{i}_{Qm} = \sqrt{I_n^2 - \mathbf{i}_{Pfrt}^2}$
end if

As in the case of reactive power support where the requirements for the reactive current are defined by Fig. 1, the active and reactive current requirements of the proposed strategy need to be defined. Fig. 4c and 4d illustrates the requirements of active and reactive current respectively. According to the proposed requirements, if the voltage exceeds the dead-band zone defined as $0.9 \leq V_{PCC} \leq 1.1$ pu, the active and reactive currents are altered according to the intensity of the voltage drop.

TABLE I
DESIGN PARAMETERS OF THE GSC.

GSC nominal Values	V_n=400 V, f_n=50 Hz, S_n=8 kVA,V_{DC}=740 V
LC filter	L_{if}=1.5 mH, C_f= 6 μF, R_{if}=0.19 Ω, R_f=1 Ω
Sampling and PWM	$f_{sampling} = f_{pwm}$=10 kHz
PLL	k_p=92, T_i=0.000235
Current controller	k_p=25, k_i=316.67
DC-link controller	k_p=0.368, k_i=5.455

III. MODEL VERIFICATION

This section presents the implementation of the proposed voltage support scheme on a photovoltaic (PV) system and its effectiveness is validated accordingly.

A PV system enhanced with the proposed voltage support scheme is modelled in MATLAB/Simulink. The model includes a 8 kW peak PV system connected to the network through a two-level Grid Side Converter (GSC) based on Insulated Gate Bipolar Transistors (IGBTs). The controller is implemented in the synchronous domain (dq frame). Fig. 5 shows the detailed model of the PV system. The technical characteristics of the PV system are provided in Table I.

The system includes two operational modes: a) normal operation mode and b) FRT mode. In the normal operation, the system injects the maximum available active power to the grid while the reactive power is set to zero. However, during the FRT mode, the active and reactive reference currents are estimated by the proposed scheme. The operation modes are enabled according to a signal generated from the voltage sag detection block.

In case of normal operation, the PV system extracts all the available power from the solar potential. This was implemented with a perturb and observe (P&O) MPPT algorithm. More advanced MPPT algorithms do exist, but investigating the long-term dynamics of the system is out of the scope of this work. The output of the MPPT is fed into the V_{DC} controller that is responsible to maintain a constant DC voltage. Variations on the DC-link voltage can introduce oscillations in the active power and also deteriorate the lifespan of the capacitor, hence achieving a constant DC-link voltage is important. The DC voltage controller is implemented with proportional integral (PI) controllers, which are tuned with the symmetrical optimum method as described in [16]. Thereafter, the output of the V_{DC} controller is fed to the current controller. A conventional current controller with PI regulators and a conventional dqPLL [10] is used since only balanced voltage drops and harmonic-free grid conditions will be investigated in this paper. However, in case where unbalanced voltage drops or harmonic distorted conditions are of interest, it is recommended to use advanced current controllers for positive and negative sequence [17] and advanced PLL based synchronisation methods [9].

In case where the PV system operates in the FRT mode, the MPPT and V_{DC} controllers are switched off since the system should be moved to a non-MPPT point. Then, the voltage support block provides the current references according to (4).

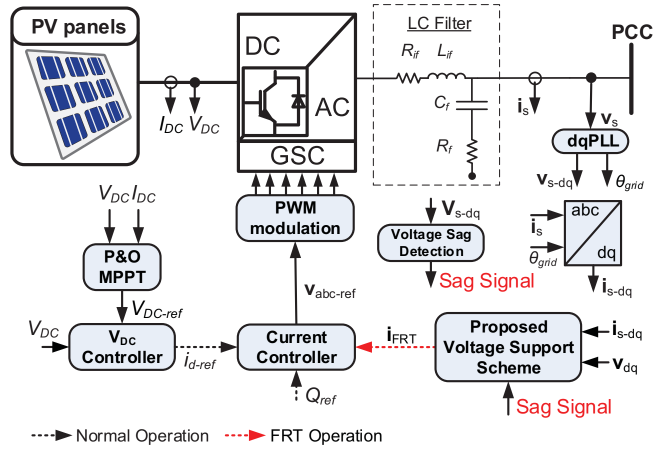

Figure 5. PV model enhanced with the proposed voltage support.

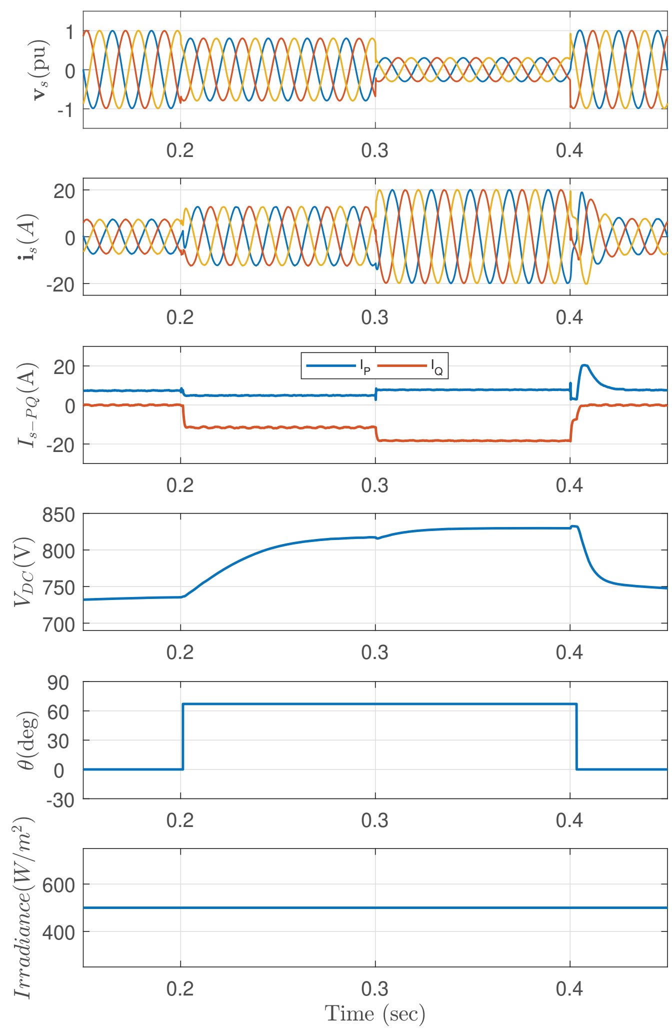

Figure 6. Simulation results for the PV system in voltage support mode during operational mode 2 for a three-phase balanced fault.

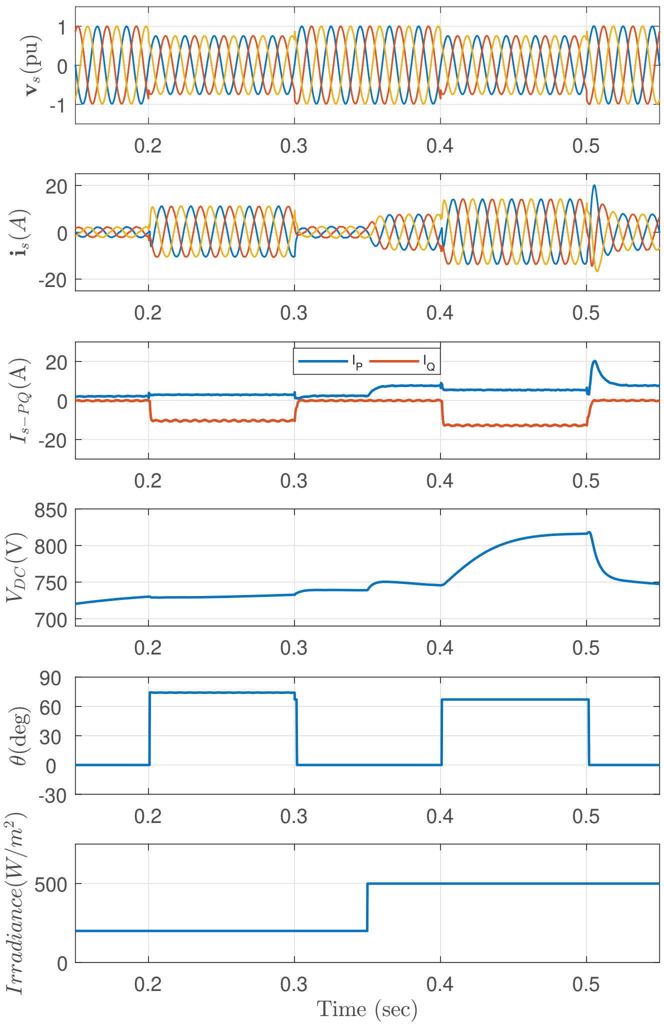

Figure 7. Simulation results for the PV system in voltage support mode during operational mode 3.

As can be seen, the proposed scheme utilises the knowledge of the grid impedance. In this case study the X/R ratio is assumed that is known a priori however, there are various methods that can be utilised to estimate the grid impedance [18]–[20]. The estimation of the X/R ratio will be considered in future work.

The simulation results of the PV system enhanced with the proposed voltage support scheme are discussed below. In the first scenario two balanced grid faults with 20% and 70% voltage drop occurred at $0.2 < t < 0.3$ and $0.3 < t < 0.4$ respectively, as shown in Fig. 6. In this case study, a constant irradiance is considered and a $k = 2$ droop constant is used. As it can be seen, the current during the FRT is consisted by active and reactive currents. During the first voltage drop ($0.2 < t < 0.3$) the converter injects a current $\mathbf{i}_{FRT}$ that is proportional to the voltage drop intensity. When the voltage drop at $0.3 < t < 0.4$ is applied, the converter current reaches the rated current of the converter since $k = 2$ and the voltage drop is more than 50%. The FRT current angle (θ) can validate the operation of the proposed strategy. During the normal operation, the angle is zero since only active power is delivered to the grid. When the voltage support mode is enabled for $0.2 < t < 0.4$, the angle is maintained constant at its optimum value which represents the operation mode 2 described in Section II-C since $\mathbf{i}_{Pm} > i_{P_{frt}}$. Further, the DC-link voltage is increased due to the new operating point of the PV panels that require reduction of the active power. In case where a constant DC-link voltage is required, then a chopper circuit can be implemented to consume the excess energy; however, this is not considered in this work.

A second case study is investigated to validate the operation 3 of the PV system as outlined in Section II-C. In this scenario, a voltage drop of 25% for $0.2 < t < 0.3$ and $0.4 < t < 0.5$ is applied at the MV grid. The PV system is initially operating with irradiance 200 W/m^2 and at $t = 0.35$ s is increased to 500 W/m^2. During the first voltage drop ($0.2 < t < 0.3$) the GSC currents are set according to the proposed strategy. The active current is maintained constant since $\mathbf{i}_{Pm} < i_{P_{frt}}$ and only the reactive current is altered according to the intensity of the voltage drop. Hence, the PV system operates in operational mode 3, which can also be seen from the current angle that is slightly different than the optimal. However, for $0.4 < t < 0.5$, the available power is increased due to the variation of the irradiance at $t = 0.35$ s. Therefore $\mathbf{i}_{Pav} > i_{P_{frt}}$ and the optimum angle current is maintained.

IV. Evaluation in a Realistic Distribution Grid

This section investigates the impact of the proposed voltage support methodology on the operation of the distribution network. A radial low voltage network is modeled in MATLAB/Simulink to represent a realistic distribution network as shown in Fig. 8. The system includes three PV/load buses and five load buses. The PV systems are modified according to the proposed voltage support scheme based on knowing the grid impedance.

The performance of the proposed voltage support scheme is evaluated by performing three scenarios. These include: (a) disconnection of the PV systems during the fault (base scenario), (b) injection of reactive power support according to [10] and (c) provision of voltage support according to the proposed methodology. A voltage drop is generated at the medium voltage side of the substation to investigate the voltage support across the feeder.

The evaluation of the proposed strategy was measured based on the baseline scenario (a), which is the disconnection

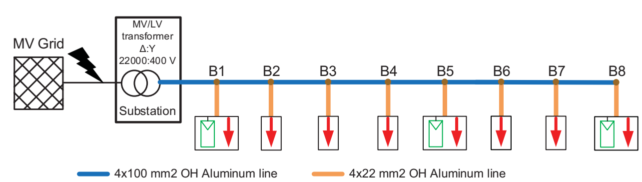

Figure 8. Radial distribution grid model with PV systems enhanced with the proposed voltage support scheme.

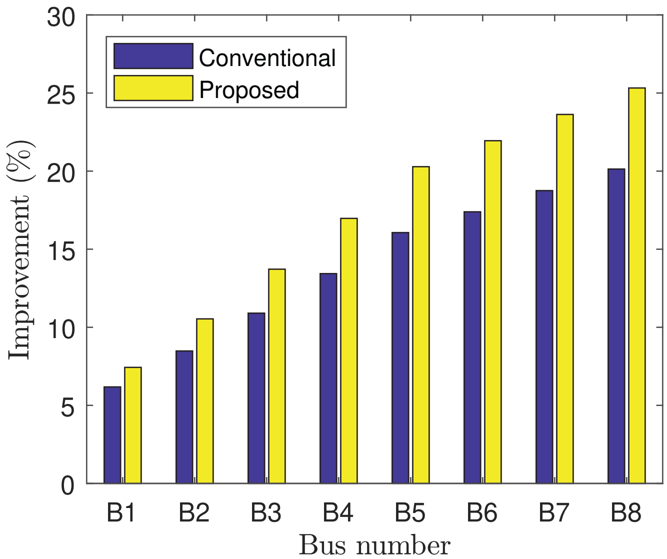

Figure 9. Evaluation of the proposed concept in a realistic distribution grid.

of the PV systems during the fault. Fig. 9 illustrates the results from the evaluation of the reactive power support (conventional) and the proposed voltage support in a realistic distribution grid. The average voltage improvement of the proposed voltage support scheme was 17.5%, while with the reactive power support scheme was only 13.9%. The proposed strategy improves the voltage from 7% at B1 up to 25% at B8 and the conventional method from 6% up to 20% respectively. Therefore, the proposed voltage support scheme has a beneficial impact on the operation of the distribution grid and the stability of the grid is improved. In addition, as the penetration level of DGs is increasing, it is critical to provide the maximum support to the distribution network since it would be more vulnerable to disturbances. Hence, the proposed strategy provides the maximum voltage support to the feeder.

V. Conclusions

This paper proposes a voltage support scheme for low voltage distribution network during faults. The methodology utilizes the grid impedance knowledge to estimate the injected active and reactive power that provide the maximum benefit to the voltage. In addition, the active and reactive currents are altered with a droop curve according to the intensity of the voltage drop. A PV system is used to demonstrate the operation of the proposed scheme using simulations. Further, the effectiveness of the proposed methodology on the operation of the distribution system is evaluated with simulations. The results indicate that the proposed voltage support scheme outperforms the existing practices and can improve the stability of the low voltage distribution grid.

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