INTEGRATION OF PV AND DVR SYSTEMS FOR MODERN LOAD CENTRE

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ABSTRACT *-This paper presents a new system configuration for integrating a grid-connected photovoltaic (PV) system together with a self-supported dynamic voltage restorer (DVR). The pro- posed system termed as a "six-port converter," consists of nine semiconductor switches in total. The proposed configuration retains all the essential features of normal PV and DVR systems while reducing the overall switch count from twelve to nine. In addition, the dual functionality feature significantly enhances the system robustness against severe symmetrical/asymmetrical grid faults and voltage dips. A detailed study on all the possible operational modes of six-port converter is presented. An appropriate control algorithm is developed and the validity of the proposed configuration is verified through extensive simulation as well as experimental studies under different operating conditions.*

Index Terms—Power Quality, Bidirectional Power Flow, Voltage Control, Distributed Power Generation, Photovoltaic (PV) Systems.

I. INTRODUCTION[1]

The fast depletion of conventional energy resources and increasing environmental concerns has made renewable energy resources, such as photovoltaic (PV) and wind, progressive sources of electric power generation. Since power generated by a PV source is principally dc, it requires a dc–ac inversion stage for grid-connected operation. The main component of a grid-connected PV system is generally the three phase voltage source inverter (VSI) having six switches in total. Its primary function is to enhance the injected active power through maximum power point tracking (MPPT) control of PV array. On the other hand, with the increased penetration of sensitive loads, the power quality issues in the modern distribution system have significantly increased. Most frequent and serious disturbances in the grid voltage are sags, swells, and faults. To maintain uninterrupted voltage at load terminals, various custom power devices are used among which DVR is considered as the most effective and comprehensive solution.

The proposed configuration for integrating a conventional grid-connected PV system self supported DVR is proposed. The proposed configuration exhibits all the functionalities of existing PV and DVR system as well as enhances the DVR operating range. It allows DVR to utilize active power of PV plant and thus improves the system robustness against the severe grid faults. The proposed configuration could be very useful for modern load centers where on-site PV generation and strict voltage regulation are required. System will be modeled using MATLAB/SIMULINK.

It is likely that the modern load centers would be equipped with on-site PV generation unit(s) as well as custom power device(s) for critical load protection. Fig. 1 shows such a system configuration where a grid-connected PV plant injects active power through six-switch VSI (PV-VSI) while self-supported DVR performs voltage sag compensation for sensitive loads using second six-switch VSI (DVR-VSI). During the occur rence of fault/deep sag at the point of common coupling (PCC), these independent PV and DVR systems face major operational limitations. In this scenario, the self-supported DVR can no longer maintain the rated load voltage due to finite energy in dc-link capacitor. Similarly, the active power produced by PV plant cannot be supplied to the grid. One possible solution for DVR is to keep the dc-link capacitor charged at rated value through a shunt rectier connected at load side. However, this configuration faces large VA loading of DVR-VSI, which must be rated for both load and shunt rectifier VA. Another way to enhance the DVR performance is to replace the dc-link capacitor with a battery energy storage system. Although, it does not affect DVR rating but incurs additional battery maintenance issues. The VA rating of centralized PV inverter depends on the installed capacity of PV solar panels. This inverter VA is generally underutilized due to intermittent nature of solar power especially during late evening hours, night hours, and early morning hours where it remains idle. On the other hand, the DVR VA rating is typically 20%–40% of the total load VA loading. The DVR inverter also has low-utilization factor as the voltage disturbance is a short duration power quality issue and does not occur frequently.

By combining the above two applications, in this paper, a new six-port converter-based system configuration is proposed for integrating on-site PV generation unit and DVR as shown in Fig.2. The proposed configuration eliminates the requirement of two separate inverters for PV and DVR applications, reduce the switch count of conventional system by 25% and most importantly overcomes the above-mentioned operational limitations associated with conventional PV and DVR systems.

The proposed configuration could be useful for low to mediumpower load centers/factories with sensitive loads and considerable onsite PV generation capacity (more than 50% of the load requirement). Under this consideration, the VA rating of PV system will govern the overall VA rating of six-port converter, which means that equally rated (as of PV system) DVR is available for load voltage regulation. In the literature, the six-port converter is reported as a replacement of traditional back to back converters for dual motor drives, rectifier-inverter systems, uninterruptible power supplies, UPQC , and for microgrid applications. Fault ride through enhancement of DFIG- based wind energy conversion system using nine switch-based converter is also reported recently. Nevertheless, the proposed configuration of Fig. 2 retains all the essential features of traditional 12 switch system in Fig. 1. It replaces the two dissimilar VSIs with one integrated converter while reducing the overall semiconductor count, gate drive, and control circuitry (by 25%). Furthermore, the configuration allows bidirectional active power flow between six-port converter, PV plant, and utility grid, a feature that provides seamless sag com pensation to protect sensitive loads during severe voltage dips at PCC. The proposed work is evaluated by detailed simulation study and finally, validated experimentally.

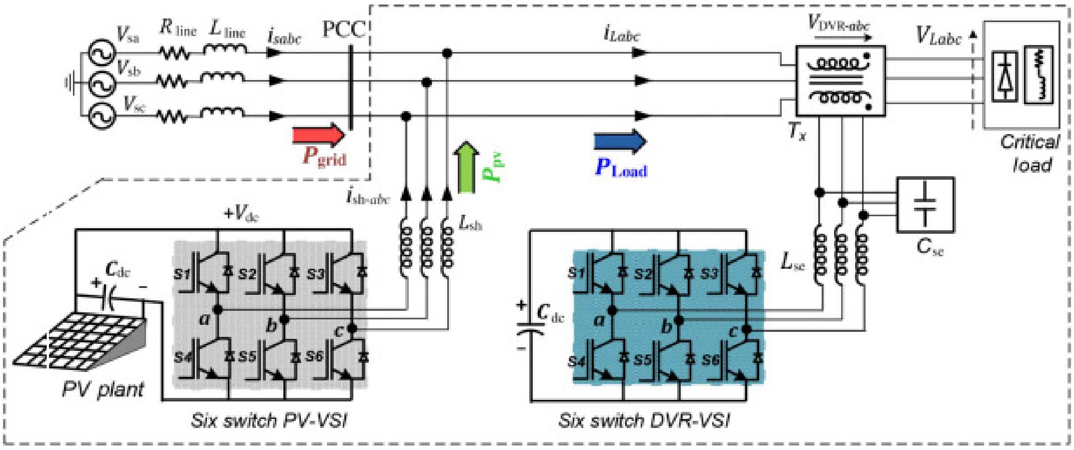

Fig. 1. On-site PV generation and sensitive load protection using self-supported DVR system.

II. PROPOSED INTEGRATED PV-DVR SYSTEM CONFIGURATION

The proposed system configuration is shown in Fig. 2. In this configuration, nine semiconductor switches are used to realize PV and DVR operations simultaneously. The main difference between the proposed configuration and the system given in Fig. 1 is the dual output six-port converter whose six out-ports is divided into two set of outputs. The left three ports connected to PCC are designated as the output of PV-VSI, whereas the right three ports {x,y,z} are designated as output of DVR-VSI. Switches $S4-S6$ are shared between PV and DVR VSIs. Based on the grid condition and PV plant status, the six-port converter can operate in one of the various operational modes as given in Table I.

A. Mode-1 (Healthy Grid Mode)

Mode-1 reflects the normal operation of six-port converter when the grid voltage is at nominal value and PV plant is operating at standard atmospheric condition (SAC). During *Mode-1*, PV-VSI injects the active power generated by PV plant in the grid while DVR-VSI remains inactive as the grid is healthy.

B. Mode-2 (Fault Mode)

Mode-2 corresponds to a condition when there is a three-phase fault at PCC. During this mode, PV-VSI remains inactive while DVR-VSI injects the maximum compensating voltages (V_{Labc}^*).

C. Mode-3 (Sag Mode)

Mode-3 considers the operation of six-port converter during voltage sag at PCC. In this mode, the DVR-VSI performs the pre-sag compensation to avoid premature tripping of critical load due to large phase jump. Since the grid voltage is nonzero, the PV plant contributes to inject limited active power based on the maximum current capacity, i.e., both DVR and PV-VSI (all nine switches) are active during Mode-3.

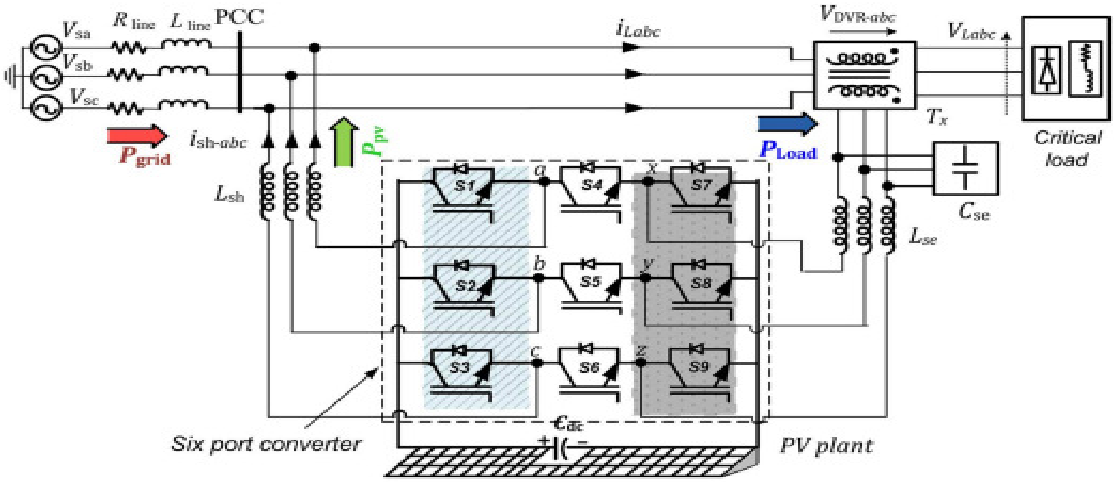

Fig. 2. Proposed configuration of integrated PV and DVR systems

D. Mode-4 (No PV Generation)

Mode-4 corresponds to the operation of six-port converter when PV plant does not provide any active power and remains inactive (during early morning hours, late evening hours, fully cloudy day, and throughout night hours). In the absence of PV plant, the role of PV-VSI is reversed. It remains idle as long as the grid is operating at rated voltage and draws active power from grid during sag intervals to keep the dc-link capacitor charged at rated value.

In the case of severe or deeper sag depths where the current requirement exceeds the switch current rating, the dc-link regulation cannot be performed.

III. OPERATING PRINCIPLE AND MODULATION SCHEME FOR SIX-PORT CONVERTER

The six-port converter has three switches shared between PV and DVR-VSIs. It, therefore, faces restriction on the allowable switching states. The two output ports on the same leg can have four possible connections.

1) Both outputs connected to $+V_{dc}$ (for phase-a: S_1-ON, S_4-ON, and S_7-OFF);
2) both to 0 V (for phase-a: S_1-OFF, S_4-ON, and S_7-ON);
3) left port to $+V_{dc}$ and right port to 0 V (for phase-a: S_1-ON, S_4-OFF, and S_7-ON); and
4) left port to 0 V and right port to $+V_{dc}$ (for phase-a: S_1-ON, S_4-ON, and S_7-ON).

The last combination, however, cannot be realized as it will result in direct short-circuiting of dc link. To achieve modulation, both the reference signals are compared with a common carrier for generating the gate pulses. In the common carrier band, the modulation reference signal of left port is placed above that of right using third harmonic injection method with no impact on output (line voltages) of six-port converter. To prevent the dc-link short circuit (due to combination 4), the crossover between two modulating reference signals should be avoided.

Two types of operations of six-port converter are possible to overcome the aforementioned limitation.

1) Equal frequency (EF) operation, where both set of outputs (i.e., $V_{pv\text{-}abc}$ and $V_{dvr\text{-}xyz}$) must operate at same frequency with small inter phase difference.

2) Variable frequency (VF) operation, of both set of outputs. This operation is more flexible as there is no constraint on the output frequency and could be useful for harmonic compensation. However, the sum of modulation references for left and right port must not exceed unity. VF operation requires doubling of dc-link voltage to prevent reference crossover.

During the normal mode, PV-VSI injects active power into grid while DVR-VSI is idle (Mode-1). The modulation index is unity for PV-VSI and zero for DVR-VSI. During sag (Mode-3) the PV-VSI continues to inject active power similar to Mode-1, but at a reduced modulation index, as the PCC voltage is reduced due to voltage sag. This facilitates the DVR-VSI to attain higher modulation index (required to compensate the sag). The increase in DVR-VSI reference is always accompanied by the corresponding decrease in PV-VSI reference and hence the crossover does not happen. Thus, the proposed configuration naturally overcomes the limitation of reference crossover.

Mode	PV status	Grid condition	Switch status		Six-port converter operation	
			Always "ON"	PWM	PV-VSI	DVR-VSI
1	Active	Healthy $V_{pcc-p.u.} = 1$	S_7–S_9	S_1–S_6	Active ($P_{PV\text{-}VSI} > 0$)	Idle ($PQ_{DVR\text{-}VSI} = 0$)
2	Active	Fault $V_{pcc-p.u.} \approx 0$	S_1–S_3	S_4–S_9	Idle ($P_{PV\text{-}VSI} = 0$)	Active ($PQ_{DVR\text{-}VSI} = PQ_{LOAD}$)
3	Active	Sag $0.1 < V_{pcc-p.u.} < 0.95$	None	S_1–S_9	Active ($P_{PV\text{-}VSI} > 0$)	Active ($PQ_{DVR\text{-}VSI} < PQ_{LOAD}$)
4	Inactive	Any of the above 3	None	S_1–S_9	Active ($P_{PV\text{-}VSI} < 0$)	Active

Table I - Proposed configuration of integrated PV and DVR systems: Different modes of operation

IV. PROPOSED TOPOLOGY

Parameter	Value
Grid voltage (L–L) (rms) V_{base}	415 V
Line frequency	50 Hz
Nominal PV power (Base kVA)	10 kVA
Nominal load power	10 kVA
Nominal load power factor	0.8 lagging
DC link voltage	700 V
DC link capacitance	3000 µF
Maximum shunt current, (I_{sh-max})	20 A
Series transformer rating/turn ratio	10 kVA/ 1:1
Filter inductor L_f and capacitance C_f	5 mH and 50 µF
Grid impedance Z_{line}	$0.5 + j0.05\ \Omega$

TABLE II – SYSTEM PARAMETERS USED FOR SIMULATION STUDY

To achieve the above operation in the proposed configuration, the pulse width modulation (PWM) technique is used. The switching operation is as given in the Table I. The Simulink model in MATLAB provides a graphical user interface, user can call the standard library module from where the necessary blocks and components are selected and are properly connected to form the dynamic system model.

V.CONCLUSIONS

The proposed configuration is the integration of a conventional grid-connected PV system and a self supported DVR. The proposed work exhibits all the functionalities of existing PV and DVR system as well as enhances the DVR operating range. It lets DVR to utilize active power of PV plant and thus improves the system robustness against severe grid faults. The proposed integration can operate in different modes based on the grid condition and PV power generation. The modes discussed here are the healthy mode, sag mode, and PV inactive mode. The simulation study demonstrates the effectiveness of the proposed configuration and its practical feasibility to perform under different operating conditions. The proposed configuration can be very useful for modern load centers where on-site PV generation and strict voltage regulation are required.

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