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Effective utilization of unified power quality conditioner for interconnecting PV modules with grid using power angle control method

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ABSTRACT

This paper proposes the effective utilization of unified power quality conditioner (UPQC) for interconnecting the PV modules to the grid using power angle control (PAC) method. A shunt active power filter (APF) is used to evacuate the power from the photovoltaic module in addition to compensating the current harmonics, load unbalance and reactive power. To accomplish this the series APF in the UPQC is used for supplying a part or whole reactive power required by the load in addition to compensating the sag, swell, supply voltage unbalance and distortions. This is made possible by controlling the phase angle and magnitude of series injected voltage called power angle control method. The reactive power and voltage compensation technique introduces a phase shift between the load terminal voltage and source voltage. The transient due to sudden phase shift is minimized using step by step introduction of series compensation voltage. The proposed method effectively utilizes the shunt APF and series APF in the UPQC for interconnecting the PV module to the grid. The simulation results from MATLAB/SIMULINK are discussed to validate the developed method.

1. Introduction

The current power distribution networks face huge reactive power requirement and poor power quality issues due to inductive loads and increased use of power electronics controlled loads respectively. However, the same advancement in power electronic devices provides solutions for reactive power compensation and power quality improvement in the form of active power filters (APFs). The UPQC is the most widely used active power filter in distribution networks to solve both current and voltage related disturbances. The other issue of ever increasing demand for electricity necessitates the interconnection of small renewable energy source based power plants to the distribution network [1–5]. The important problems of renewable sources are discontinuous generation and season based availability. To overcome these drawbacks, the interconnection of all possible renewable sources with the distribution network is mandatory. For achieving these without losing power quality, expensive power electronic switches with advanced controllers are required [6,7]. The combination of power quality improvement and interconnection of distributed renewable energy sources results in effective utilization of UPQC and cost saving [8–12]. The configuration of the proposed system with UPQC is shown in Fig. 1. The UPQC consists of both shunt and series active power filters. Thus, it has two 3-phase Voltage Source Inverters (VSIs) connected back to back sharing a common DC bus capacitor. In a conventional UPQC the current disturbances (harmonics), load unbalance and reactive power are compensated by shunt APF. Voltage related problems like voltage sag, swell and distorted supply voltage are compensated by series APF. To optimize the rating of shunt APF, a partial amount of reactive power is compensated by series APF using coordinated power angle control method [13,14]. This paper proposes the effective usage of power angle control method for interconnecting PV modules with grid without losing the ability of UPQC as active power filter. The amount of reactive power compensation shifted from shunt to series APF by power angle control method is effectively used for interconnection of PV modules to the grid through shunt APF. Before interconnecting the PV module to the grid, the full reactive power requirement of the load is compensated by shunt APF. The series APF will address only voltage related (sag, swell and source voltage harmonics) compensation. During this mode, the injected voltage from series APF is in phase with the line current so that no reactive power is involved for voltage compensation. The injected voltage from series APF during the PV module interconnection mode will neither be in phase nor in quadrature with the line current. Therefore both active and reactive power transactions are involved. The shunt APF evacuates the power from the PV module

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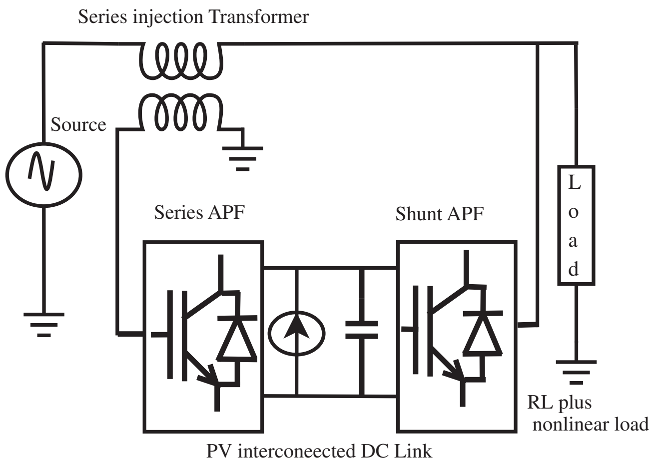

Fig. 1. System configuration.

in addition to compensating the current harmonics and DC link voltage maintenance for power flow balance. This paper proposes a proper control and instantaneous computation of magnitude and injection angle of series APF. This supports the part or full load reactive power compensation from series APF. Thus the shunt APF is used for interconnection of PV module and current harmonics compensation. The coordinated reactive power compensation control also maintains constant or desired load voltage magnitude. The maximum reactive power shared by the series APF is based on the maximum sag/swell voltage compensation required at any instant by the series active filter. The mathematical analysis of the power angle control method is discussed in [13,14]. For avoiding the maximum load swing during the start of series APF, a step by step method of introducing the phase shift is then proposed [15,16]. In the next section the extension of power angle control method for PV module interconnection is discussed.

2. UPQC control strategy with power angle control

The compensation of voltage sag/swell can be done by introducing a voltage through series APF. The injection angle can be any of the following three cases. (i) 0° (ii) 90° and (iii) any angle θ between 0° and 90° [17,18]. The case (i) requires very less voltage magnitude compared to other two cases but involves active power transaction with the line. The case (ii) requires higher voltage magnitude due to 90° injection angle. This case does not involve any real power sharing with the line, but reactive power sharing is involved. The case (iii) is minimum VA method in which the injection angle is neither 0° nor 90° [19]. Therefore, it involves real and reactive power transaction. This case is extended and used for reactive power compensation of the load via series APF by controlling both the injection voltage magnitude and angle. This is in addition to sag/swell compensation. Due to the series voltage injection, a phase difference (δ) is created between source and load voltage. The angle δ is called power angle. The compensation of reactive power along with voltage sag/swell by proper control of δ and series voltage injection magnitude is called power angle control method. The injection angle of the series injected voltage is not in quadrature with the load or source current. The magnitude and injection angle is controlled in such a way that the resultant load voltage magnitude is equal to the source voltage or any desired voltage. Fig. 2 shows the phasor representation of power angle control method. The series injected voltage V_{sr} from the series APF creates a phase difference (δ) between the source and load voltage. Due to the leading load voltage the load current also advances by the same angle δ. With reference to source voltage the source current phase angle difference is reduced thereby and the required load reactive power compensation is reduced. From Fig. 2, the magnitude of injected voltage $|V_{sr1}|$ and injection angle ϕ_{sr1} are derived in [13,14] and written as,

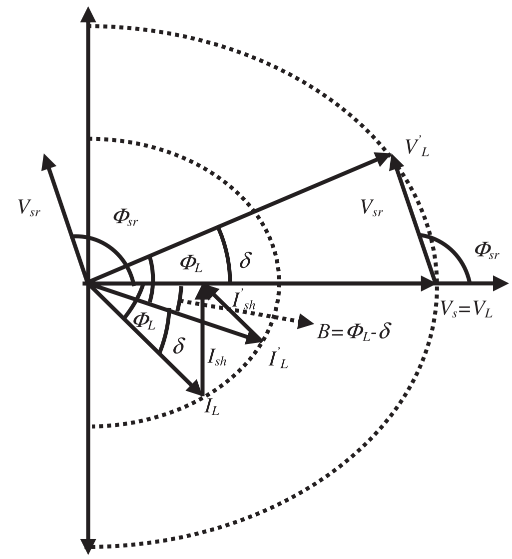

Fig. 2. Power angle control representation.

$$|V_{sr1}| = V_s\sqrt{2(1-\cos\delta)} \tag{1}$$

$$\phi_{sr1} = 180^o - \tan^{-1}(\sin\delta/(1-\cos\delta)) \tag{2}$$

where δ can be found as following,

$$\delta = \sin^{-1}(P_L - P_{pv}) \tag{3}$$

In above Q_{sr} is the reactive power to be supplied by series APF during interconnection mode and P_L and P_{pv} are the load average power and solar PV power respectively.

2.1. Series APF control

The source voltage (pu) is passed through phase locked loop for getting the fundamental frequency (*f* in HZ), phase angle and unit amplitude *Sin* ωt and *Cos* ωt signals. The source voltage is transformed to *dq0* frame using *dq0* transformation matrix for comparing with the direct axis reference voltage V_m as given by [20]. The error component will have sag/ swell and supply voltage harmonics. The error component is the reference signal in *dq0* axis for series APF during normal mode of operation. This error component will be transformed to *abc* coordinates using inverse *dq0* transformation matrix and compared with series APF output voltage for PWM pulse generation of series APF inverters. During the interconnection mode, in addition to the sag/swell and supply voltage harmonic components, the $V_{sr1}\angle\phi_{sr1}$ is also added. Thus, the reference component will have sag/swell component and load reactive power compensating component. This is explained in Fig. 3. For the normal mode the series APF reference voltage is calculated by subtracting the desired load voltage magnitude V_m from the *dq0* transformed source voltage.

$$\begin{pmatrix} v_d \\ v_q \\ v_o \end{pmatrix}_{ref} = \begin{pmatrix} v_d \\ v_q \\ v_o \end{pmatrix} - \begin{pmatrix} V_m \\ 0 \\ 0 \end{pmatrix} \tag{4}$$

After getting V_{dqoref} from Eq. (4) the reference voltage is transformed into *abc* coordinates as $V_{sr2}\angle 0$. These components are used