Operation of Parallel Inverters for Power Quality Enhancement and Interfacing Distributed Energy Resources

B. Uday kumar  
Electrical & Electronics Engineering  
SVU College of Engineering  
Tirupathi, India

Prof. A. Lakshmi Devi  
Electrical & Electronics Engineering  
SVU College of Engineering  
Tirupathi, India

Abstract—The work done in this paper is mainly focused on integration of renewable energy sources to utility grid simultaneously with enhanced power quality using parallel inverters. Two voltage source inverters (VSI) are connected in parallel at load point i.e., point of common coupling (PCC) for power quality enhancement and interfacing renewable energy source to utility grid. One VSI is operated in voltage control mode (VCM) and the other one is operated in current control mode (CCM). Load terminal voltage at desired magnitude is regulated by VSI operating in VCM, whereas VSI operating in CCM connects distributed energy resource to utility grid. Switching algorithm for VSI is derived using dead beat control.

Keywords—Voltage source inverter, Voltage control mode, Current control Mode, Voltage regulation.

I. INTRODUCTION

The load system connected to the utility grid system are mainly unbalanced inductive and nonlinear loads. Such a load profile not only increases the energy loss but also corrupt the current waveforms deteriorating the quality of power. Moreover excessive dependence on fossil fuel and ever increasing demand for energy has widen the demand supply gap subject to the fact that rate of consumption of fossil fuels is far more than the rate at which they get replenished. Fossil fuels like coal, natural gas and oil are not only exhaustible but are also known to have disastrous environmental and health consequences. This has diverted the attention from fossil fuels to renewable sources of energy like the sun, wind, tidal energy etc. Most renewable source are distributed in nature, there-by eliminating the necessity for transmitting energy over long distance, these distributed energy resource (DER) will reduce the stress on conventional power system network. Available renewable energy sources can be grouped to from microgrid. Energy available can be pumped to utility grid by synchronizing microgrid to it.

This paper presents a power electronic interface which brings the solution to both the power quality and renewable energy source. Customary approach is [6] adopted to address power quality issues which are mainly due to harmonic currents is either bypass harmonic currents, block them from entering into power system, or to compensate them by locally supplying harmonic currents. Active filtering is done in [2] using custom power devices to inject current/voltage or both into system such that undesired harmonic components gets compensated. In order to address power quality issues and to inject real power, two inverters are connected in parallel shown in fig. 1. One inverter operates in voltage control mode (VCM) and second inverter operates in current control mode (CCM).

Fig 1. Single line diagram of suggested scheme

Though solution for same problem are suggested by extending the series-shunt compensation techniques usually employed by using custom power devices in [10] these suggested solutions employs an injection transformer to take care of series compensation which results in more losses compared to shunt compensation technique alone.

The operating algorithm of the VSI operating in VCM ensures that irrespective of the distortion or unbalance in the source voltage and non-linearity in load currents balanced fundamental sinusoidal voltages are maintained at point of common coupling (PCC). The VSI operating in CCM used only for interfacing DER to utility grid. CCM inverter injects real power at PCC. The common DC-link voltage can be derived from the renewable energy source in microgrid. VSI operated in VCM is rated for reactive power, whereas inverter operated in CCM has rated for active power.

II. MODELING OF VOLTAGE SOURCE INVERTER

A. VSI In Voltage Control Mode

In this section operation of VSI in voltage control mode is explained. A conventional power system is mostly interconnected. Hence there are more chances that voltage profile at particular bus get unbalanced or distorted due to nature of load at that particular bus or also due to disturbances at any part of the system. VSI can be used to maintain voltage at PCC at a pre-specified value. VSI is realized by two level neutral-clamped voltage source converter (VSC) and connected at PCC shown in Fig. 2. Here PCC may referred as terminal. A filter capacitor (Cf) is used in parallel with the VSC.
circuit to provide a path for the high-frequency components. Here $v_{sh}, R_{sh}, L_{oi}$ are thevenin’s equivalent, where $i$ is phase a, b, c. By controlling injected currents $i_{fin}, i_{ftb}, i_{fic}$ VSI achieves its objective.

![Fig. 2. Voltage source inverter circuit connected at PCC](image)

This scheme facilitates independent control on VSI each leg. Therefore single-phase modeling of VSI is sufficient to realize the operation. A single phase equivalent of VSI connected at PCC is shown in fig. 3. A detailed state space model of VSI in VCM mode is obtained and used to derive control signals.

![Figure 3. Single phase equivalent of VSI connected at PCC](image)

It is considered that VSI and L-C filter can regulate voltage and injects currents at PCC. Here $v_{dc}$ is the average voltage, $u$, a control variable, is considered as $u_{cv}$, Control variable can be either -1 or +1 depends on switching state. Both switches in one leg is operated in complementary manner, i.e. if upper switch is in ON then lower switch is OFF state, control signal $u = +1$ and vice versa. Current through inductor and voltage across capacitor are taken as state variables, therefore two state variables are $v_{fc}$ and $i_{fc}$. State space equations given as follows:

$$\frac{dv_{fc}}{dt} = \frac{1}{C_{fc}}i_{fi} - \frac{1}{C_{fc}}i_{ft}$$

$$\frac{di_{ft}}{dt} = -\frac{1}{L_{f}}v_{fc} - \frac{R_{f}}{L_{f}}i_{fi} + \frac{V_{dc}}{L_{f}}u_{cv}$$

Above (1) and (2) equations are combined in standard state space equations as

$$\dot{x} = Ax + Bz$$

where,

$$A = \begin{bmatrix} 0 & 1/C_{fc} \\ -1/L_{f} & -R_{f}/L_{f} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ V_{dc} \end{bmatrix}$$

Equation (3) given continuous form, represented in discrete time form as follows:

$$x(k+1) = Gx(k) + Hz(k)$$

where, $G$ and $H$ matrix are given as

$$G = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}, \quad H = \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix}$$

From (4), capacitor voltage given as

$$v_{fc}(k+1) = G_{11}v_{fc}(k) + G_{12}i_{fi}(k) + H_{11}u_{cv}(k) + H_{12}i_{ft}(k)$$

Let $v_{ref}$ be the reference (nominal) voltage to be maintained at the PCC. So the cost function is chosen as

$$J = [v_{tref}(k+1) - v_{fc}(k+1)]^2$$

Condition for minimum cost function is

$$v_{fc}(k+1) = v_{tref}(k+1)$$

Finally from (5) and (7) reference control law can be given as

$$u_{cv}^*(k) = \frac{v_{tref}(k+1) - G_{11}v_{fc}(k) - G_{12}i_{fi}(k) - H_{12}i_{ft}(k)}{H_{11}}$$

Expression for reference voltage to be obtained to implement above equation (8). $v_{ref}$ magnitude can be chosen arbitrary. Here we chosen equal magnitude that of source voltage, but phase difference must be present between source and terminal voltage to ensure compensation of power losses in inverter done by source. Instantaneous power loss in inverter ($p_{sh}$) is given as

$$p_{sh} = v_{fca}i_{fta} + v_{fcb}i_{ftb} + v_{fct}i_{ftc}$$

Reference voltages given as

$$v_{trefa} = v_{m} \sin(\omega t - \delta)$$

$$v_{trefb} = v_{m} \sin(\omega t - 2\pi/3 - \delta)$$

$$v_{trefc} = v_{m} \sin(\omega t + 2\pi/3 - \delta)$$

Where, $v_{m}$ is required terminal voltage $\omega$ is system frequency.

Average value of inverter power losses can be calculated using a moving average filter. This power loss is passed through PI controller, which gives output phase angle $\delta$.

$$P_{sh}(t) = \frac{\int P_{sh}(t) dt}{\int P_{sh}(t) dt}$$

Control action mathematically represented as

$$\delta = K_p(p_{sh} - p_{shref}) + K_i \int (p_{sh} - p_{shref})dt$$

Fig. 4. Block diagram of voltage control
Here it is to be noted in this case DC-link voltage obtained through renewable energy is assumed constant, hence there is no voltage loop to generate $P_{shunt}$.

B. VSI in Current Control Mode

It is customary practice to connect Voltage Source Inverters (VSI) operating in current control mode (CCM) at PCC in parallel with load to cancel the distortion caused by the load, such that current drawn by the compensated load is pure balanced sinusoidal. This compensation is known as shunt compensation. Usually the main objectives in a 3 phase 4-wire system by operating VSI in CCM are:

1. Provide balanced supply current such that its zero sequence component is zero.
2. To have a predefined power factor from source.
3. Power supplied from source must be equal to average load power.

With a VSI operating in VCM connected at PCC as discussed in previous section, ensures that the objective no.1 enumerated above is met. Since one of the VSI’s connected at PCC is operating in VCM pre-defined power factor from source can’t be achieved. In case of grid-connected inverters the primary objective is to inject power. Hence the main purpose of connecting a VSI operating in CCM at PCC is to inject only real power. The circuit diagram of the system with two inverters connected in parallel is shown in the Fig. 5.

Above figure VSI operating in CCM injects real power to PCC. Whereas another VSI maintains voltage magnitude at desired value at PCC. This helps VSI in CCM to inject real power at PCC to load. The excess active power from VSI operating in CCM pumps back to source after meeting local load connected PCC.

III. SWITCHING CONTROL

As stated earlier, the switching variable $u$ can take values either $\pm 1$ depending on the switching state of the top switch and bottom switch of a leg in the inverter. The voltage across each battery unit is maintained at $V_{dc}$. In Fig. 2 S is the status of the top switch, and its complementary being the status of bottom switch in the same leg and the subscript represents the phase of the inverter. Therefore, through switching the inverter supplies a voltage $\pm V_{dc}$. This is represented as $V_{dc}u$ in Fig. 3. The Variable $u$ controls the status of the inverter switches through gate drive circuits. The switching variable $u$ is obtained from the continuous signal $u_c$ by a hysteresis action around zero.

**Table 1 System Parameters**

<table>
<thead>
<tr>
<th>System Quantity</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>Nominal Source/grid voltage</td>
<td>326.26V ±10% (peak), sinusoidal and may exhibit swell, sag</td>
</tr>
<tr>
<td>PCC/Load bus voltage</td>
<td>326.26V(Peak), sinusoidal and balanced</td>
</tr>
<tr>
<td>Feeder impedance</td>
<td>1Ω, 10mA</td>
</tr>
<tr>
<td>Load parameters</td>
<td>40Ω, 0.2 H in each phase and a 3-φ diode bridge rectifier feeding R-L load of 100 Ω, 0.2 mH</td>
</tr>
<tr>
<td>Interfacing inductors ($L_1$, $L_2$)</td>
<td>0.2 Ω, 20mA connected to each leg of both VSI</td>
</tr>
<tr>
<td>Filter capacitors ($C_f$)</td>
<td>20 μF Across each phase of VSI operating in VCM</td>
</tr>
<tr>
<td>PI controller gains</td>
<td>$K_p = 9 e^\circ$, $K_i = 11 e^\circ$</td>
</tr>
<tr>
<td>Hysteresis band ($b_{h1}$, $b_{h2}$)</td>
<td>1 V, 0.5 A</td>
</tr>
<tr>
<td>DC link Voltage</td>
<td>$V_{dc1} = V_{dc2} = 600 V$</td>
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</table>

Detailed simulation results are presented in this section. Here demonstrated that VSI is able to maintain the PCC voltage at the nominal value irrespective of voltage variations in source and load changes.

Results shown in fig. 6 are only with VSI operating in VCM connected PCC. From fig. 6(a), (b), (c), (d), (e) it can be concluded that when are at nominal value (326.26 V peak) and load current are non-sinusoidal the VSI injects filter currents filter currents as shown, to maintain voltage at PCC...
balanced 1 p.u. pure sinusoidal currents are drawn from source. It can also be observed that source currents lead respective source voltages, since reactive power is supplied by compensator/VSI to source also in addition to load.

When there is sag in the source voltage in order to maintain PCC voltage at nominal value, the VSI has to inject more current compared to the situation when source voltage is at nominal value. Fig. 6(f) (g) (h) shows source voltage, PCC voltage and filter currents with 20% sag and 20% swell in source voltage. It is clearly shown that during sag and swell filter injects more current to PCC to maintain voltage at nominal value which is shown in fig. 6(h).

When both VSI are connected at PCC, the source voltage at nominal value, with non-linearity in the load currents. So, in order to maintain 1.0 p.u. balanced sinusoidal voltage at PCC, currents \( i_{fa1}, i_{fb1}, i_{fc1} \) are injected by VSI operating in VCM as shown in fig 7(d). Hence current drawn from source are pure sinusoidal shown in (e). \( i_{fa2}, i_{fb2}, i_{fc2} \) are the currents injected by VSI operating in CCM to inject active power shown in fig 7(e).
VSI in CCM mode injects $i_{fa2}$, $i_{fb2}$, $i_{fc2}$ to inject active power at PCC. Both Filter currents VSI operating in VCM mode and VSI operating in CCM mode are shown in fig. 8 (c) and (d) respectively.

As a consequence of which $\delta$ is negative to pump remaining active power to source after meeting the local load connected at PCC. Which can be clearly observed from the above fig. 7 (g).

When source exhibits sag and swell as shown in fig. 8 (a) even though load currents are non-sinusoidal, the VSI operating in VCM injects $i_{fa1}$, $i_{fb1}$, $i_{fc1}$ to ensure that PCC voltage are pure sinusoidal and maintained 1.0 p.u. subsequently source currents are sinusoidal.

In fig. 8 (e) shows source, load and CCM active powers from figure it clearly depicts that VSI in CCM pumps excessive power to source after meeting the local load demand.
V. CONCLUSIONS

In this work, a detailed study has been done for integration of distributed energy resources to utility grid to inject real power. Simultaneously enhancement of power quality is done. To achieve above two objectives the scheme of connecting two inverters in parallel at load bus with two modes of operation is suggested. It has been shown that VSI operating in VCM able to maintain PCC voltage against load and source disturbances. Inverter operating in CCM injects only real power at PCC. If real power injected is more than load demand, rest will be pumped to source.

REFERENCES


