Grid interconnection of renewable energy sources at distribution level with power quality improvement features

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ABSTRACT

This paper presents a novel control strategy for achieving maximum benefits from the grid-interfacing inverters when installed in 3-phase 4-wire distribution systems. The inverter is controlled to perform as a multi-function device by incorporating active power filter functionality. The inverter can thus be utilized as: 1) power converter to inject power generated from RES to the grid, and 2) shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. With such a control, the combination of grid-interfacing inverter and the 3-phase 4-wire linear/non-linear unbalanced load at point of common coupling appears as balanced linear load to the grid. This new control concept is demonstrated with extensive MATLAB/Simulink simulation studies.

I. Introduction

Electric utilities and end users of electric power are becoming increasingly concerned about meeting the growing energy demand. Seventy five percent of total global energy demand is supplied by the burning of fossil fuels. But increasing air pollution, global warming concern, diminishing fossil fuels and their increasing cost have made it necessary to look towards renewable sources as a future energy solution.

In this paper the features of APF in the conventional inverter interfacing renewable with the grid, without any additional hardware cost. Here, the main idea is the maximum utilization of inverter rating which is most of the time underutilized due to intermittent nature of RES. It is shown in this paper that the grid-interfacing inverter can effectively be utilized to perform following important functions: 1) transfer of active power harvested from the renewable resources (wind, solar, etc.); 2) load reactive power demand support; 3) current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 4-wire system. Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. The PQ constraints at the PCC can therefore be strictly maintained within the utility standards without additional hardware cost [1], [2].

A. Power Quality

We can define power quality problems as: ‘Any power problem that results in failure or maloperation of customer equipment manifests itself as an economic burden to the user, or produces negative impacts on the environment.’

II.Modelling Of Case Study System

Description:

The proposed system consists of RES connected to the dc-link of a grid-interfacing inverter as shown in Fig. 1. The voltage source inverter [3] is a key element of a DG system as it interfaces the renewable energy source to the grid and delivers the generated power. The RES[4],[5] may be a DC source or an AC source with rectifier coupled to dc-link. Usually, the fuel cell and photovoltaic energy sources generate power at variable low dc voltage, while the variable speed wind turbines generate power at variable ac voltage. Thus, the power generated from these renewable sources needs power conditioning (i.e., dc/dc or ac/dc) before connecting on dc-link[6]–[8]. The dc-capacitor decouples the RES from grid and also allows independent control of converters on either side of dc-link.

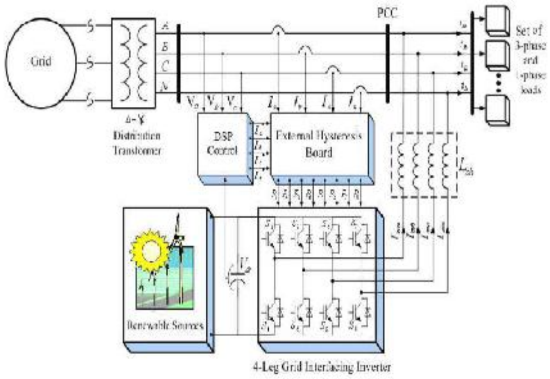


Fig.1. Schematic of proposed renewable based distributed generation system

A. DC-Link Voltage and Power Control Operation:

Due to the intermittent nature of RES, the generated power is of variable nature. The dc-link plays an important role in transferring this variable power from renewable energy source to the grid. RES are represented as current sources connected to the dc-link of a grid-interfacing inverter.

Fig. 2 shows the systematic representation of power transfer from the renewable energy resources to the grid via the dc-link. The current injected by renewable into dc-link at voltage level V_{dc} can be given as

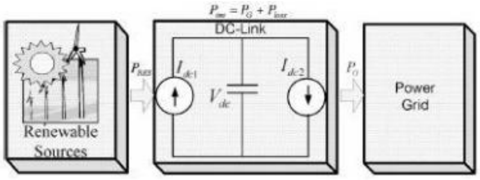


Fig. 2.1 DC-Link equivalent diagram.

$$I_{\text{dc1}} = \frac{P_{\text{RES}}}{V_{\text{dc}}} \qquad \text{............... (1)}$$

Where P_{RES} is the power generated from RES.

The current flow on the other side of dc-link can be represented as,

$$I_{\text{dc2}} = \frac{P_{\text{inv}}}{V_{\text{dc}}} = \frac{P_G + P_{\text{Loss}}}{V_{\text{dc}}} \qquad \text{……….(2)}$$

Where P_{inv}, P_G and P_{Loss} are total power available at grid-interfacing inverter side, active power supplied to the grid and inverter losses, respectively. If inverter losses are negligible then $P_{\text{RES}} = P_G$.

B. Control of Grid Interfacing Inverter:

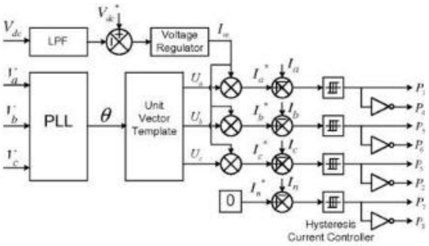


Fig.2.2. Block diagram representation of grid-interfacing inverter control.

The control diagram of grid- interfacing inverter for a 3-phase 4-wire system is shown in Fig. 3. The fourth leg of inverter is used to compensate the neutral current of load. The main aim of proposed approach is to regulate the power at PCC during: 1) $P_{RES=0}$; 2) $P_{RES}<$ total load power (P_L) ; and 3) $P_{RES} > P_L$. While performing the power management operation, the inverter is actively controlled in such a way that it always draws/ supplies fundamental active power from/ to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current. The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter injected power appears as balanced resistive load to the grid. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. Thus the output of dc-link voltage regulator results in an active current I_m. The multiplication of active current component (I_m) with unity grid voltage vector templates (U_a, Ub and U_c) generates the reference grid currents (I_a^* ,I_b^* and I_c^*). The reference grid neutral current (I_n^*) is set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle (θ) obtained from phase locked loop (PLL) is used to generate unity vector template[9],[10].

$$U_a = \mathrm{Sin}(\theta) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$U_b = \mathrm{Sin}\left(\theta - \frac{2\pi}{3}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$U_c = \mathrm{Sin}\left(\theta + \frac{2\pi}{3}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The actual dc-link voltage (V_{dc}) is sensed and passed through a first-order low pass filter (LPF) to eliminate the presence of switching ripples on the dc-link voltage and in the generated reference current signals. The difference of this filtered dc-link voltage and reference dc-link voltage (V_{dc}^*) is given to a discrete- PI regulator to maintain a constant dc-link voltage under varying generation and load conditions. The dc-link voltage error ($V_{dcerr\ (n)}$) at n^{th} sampling instant is given as:

$$V_{\mathrm{dcerr}(n)} = V^*_{\mathrm{dc}(n)} - V_{\mathrm{dc}(n)}. \qquad \ldots\ldots\ldots\ldots\ldots (6)$$

The output of discrete-PI regulator at n^{th} sampling instant is expressed as

$$I_{m(n)} = I_{m(n-1)} + K_{PV_{\mathrm{dc}}}\left(V_{\mathrm{dcerr}(n)} - V_{\mathrm{dcerr}(n-1)}\right) + K_{IV_{\mathrm{dc}}} V_{\mathrm{dcerr}(n)} \qquad \ldots\ldots\ldots\ldots \quad (7)$$

Where $K_{\mathrm{PVdc}} = 10$ and $K_{\mathrm{IVdc}} = 0.05$ are proportional and integral gains of dc-voltage regulator. The instantaneous values of reference three phase grid currents are computed as

$$I_a^* = I_m \cdot U_a \qquad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$I_b^* = I_m \cdot U_b \qquad \ldots\ldots\ldots\ldots\ldots (9)$$

$$I_c^* = I_m \cdot U_c \qquad \ldots\ldots\ldots\ldots (10)$$

The neutral current, present if any, due to the loads connected to the neutral conductor should be compensated by forth leg of grid-interfacing inverter and thus should not be drawn from the grid. In other words, the reference current for the grid neutral current is considered as zero and can be expressed as

$$I_n^* = 0. \qquad \ldots\ldots\ \ldots\ldots\ldots\ldots (11)$$

The reference grid currents (I_a^* ,I_b^* ,I_c^* and I_n^*)are compared with actual grid currents (I_a^* ,I_b^* ,I_c^* and I_n^*) to compute the current errors as

$$I_{\mathrm{aerr}} = I_a^* - I_a \qquad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$I_{\mathrm{berr}} = I_b^* - I_b \qquad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$I_{\mathrm{cerr}} = I_c^* - I_c$$ ……………… (14)

$$I_{\mathrm{nerr}} = I_n^* - I_n.$$ ……………(15)

These current errors are given to hysteresis current controller. The hysteresis controller then generates the switching pulses (P_1toP_g) for the gate drives of grid-interfacing inverter. The average model of 4-leg inverter can be obtained by the following state space equations

$$\frac{dI_{\mathrm{Inva}}}{dt} = \frac{(V_{\mathrm{Inva}} - V_a)}{L_{\mathrm{sh}}}$$ ………… (16)

$$\frac{dI_{\mathrm{Invb}}}{dt} = \frac{(V_{\mathrm{Invb}} - V_b)}{L_{\mathrm{sh}}}$$ ……….. (17)

$$\frac{dI_{\mathrm{Invc}}}{dt} = \frac{(V_{\mathrm{Invc}} - V_c)}{L_{\mathrm{sh}}}$$ ………… (18)

$$\frac{dI_{\mathrm{Invn}}}{dt} = \frac{(V_{\mathrm{Invn}} - V_n)}{L_{\mathrm{sh}}}$$ ………. (19)

$$\frac{dV_{\mathrm{dc}}}{dt} = \frac{(I_{\mathrm{Invad}} + I_{\mathrm{Invbd}} + I_{\mathrm{Invcd}} + I_{\mathrm{Invnd}})}{C_{\mathrm{dc}}}$$ ………. (20)

Where $V_{\mathrm{Inva}}, V_{\mathrm{Invb}}, V_{\mathrm{Invc}}$, and V_{Invn} are the three-phase ac switching voltages generated on the output terminal of inverter. These inverter output voltages can be modeled in terms of instantaneous dc bus voltage and switching pulses of the inverter as

$$V_{\mathrm{Inva}} = \frac{(P_1 - P_4)}{2} V_{\mathrm{dc}}$$ ………………. (21)

$$V_{\mathrm{Inva}} = \frac{(P_3 - P_6)}{2} V_{\mathrm{dc}}$$ …………….. (22)

$$V_{\mathrm{Inva}} = \frac{(P_5 - P_2)}{2} V_{\mathrm{dc}}$$ ……………… (23)

$$V_{\mathrm{Inva}} = \frac{(P_7 - P_8)}{2} V_{\mathrm{dc}}.$$ ………… (24)

Similarly the charging currents $I_{\mathrm{Invad}}, I_{\mathrm{Invbd}}, I_{\mathrm{Invcd}}$, and I_{Invnd} on dc bus due to the each leg of inverter can be expressed as

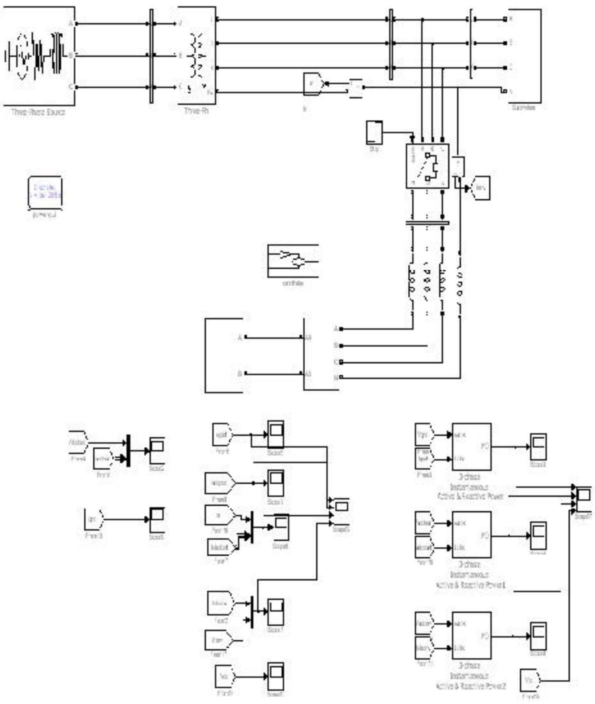
$$I_{\mathrm{Invad}} = I_{\mathrm{Inva}}(P_1 - P_4)$$ …… … (25)

$$I_{\mathrm{Invbd}} = I_{\mathrm{Invb}}(P_3 - P_6)$$ ……. ….. (26)

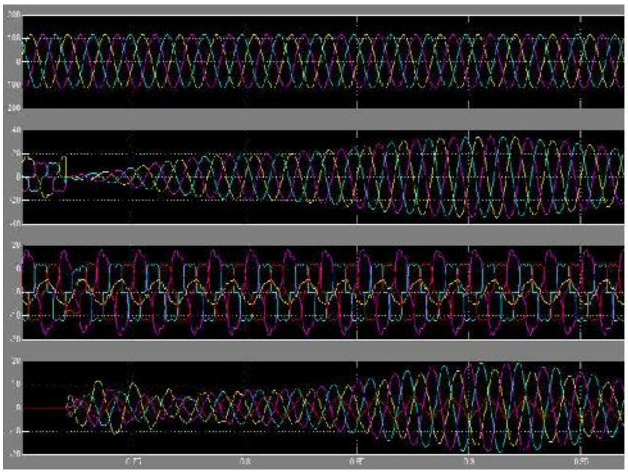
$$I_{\mathrm{Invcd}} = I_{\mathrm{Invc}}(P_5 - P_2)$$ ……… …...(27)

$$I_{\mathrm{Invad}} = I_{\mathrm{Inva}}(P_7 - P_8)$$ ………….. (28)

III.Matlab Design of Case Study



IV.SIMULATION RESULTS



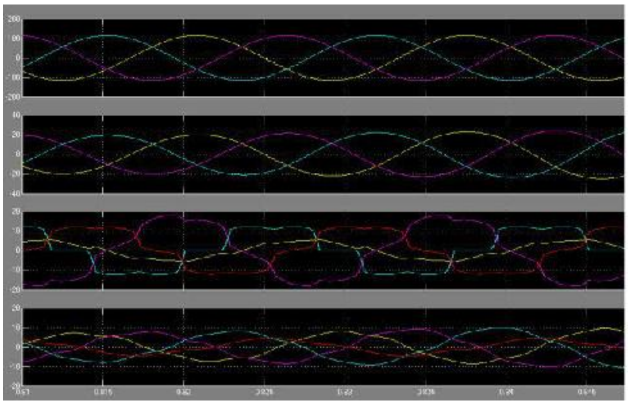


Fig.3.1 Simulation results: (a) Grid voltages, (b) Grid Currents (c) Unbalanced load currents, (d) Inverter Currents

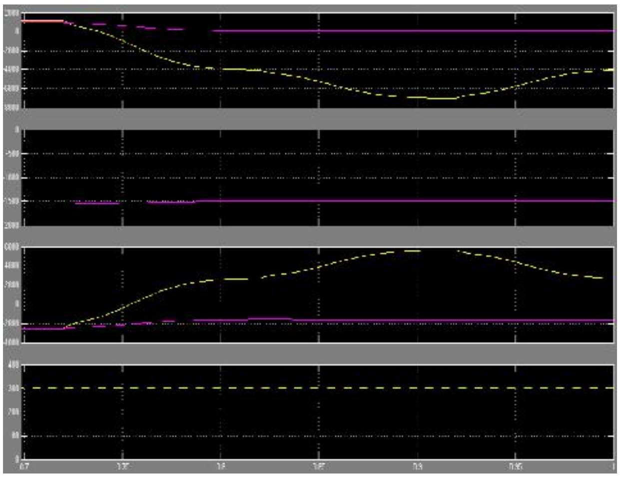


Fig 3.2. Simulation results: (a) PQ-Grid, (b) PQ-Load, (c) PQ-Inverter, (d) dc-link voltage.

V.Conclusion

This paper has presented a novel control of an existing grid interfacing inverter to improve the quality of power at PCC for a 3-phase 4-wireDGsystem.The grid-interfacing inverter with the proposed approach can be utilized to:

i) Inject real power generated from RES to the grid, and/or,

ii) Operate as a shunt Active Power Filter (APF). This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. Extensive MATLAB/Simulink simulation results have validated the proposed approach and have shown that the grid-interfacing inverter can be utilized as a multi-function device.

It is further demonstrated that the PQ enhancement can be achieved under threedifferent scenarios: 1) $P_{RES}=0$, 2) $P_{RES}<P_{Load}$, and 3) $P_{RES}>P_{Load}$. When the power generated from RES is more than thetotal load power demand, the grid-interfacing inverter with theproposed control approach not only fulfills the total load activeand reactive power demand (with harmonic compensation) butalso delivers the excess generated sinusoidal active power tothe grid at unity power factor.

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