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Inverters Synchronization of Distributed Renewable Energy Resources

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Abstract- **A grid connected inverter must provide a sinusoidal AC waveform which remains stable and also matches voltage and grid frequency according to defined standards. A non-synchronized or poorly synchronized inverter can lead to imbalances in load, can cause damage to equipment, grid instability, and even power outages in the grid itself. The problem become more significant if inverters of renewable resources are of distributed nature and connected to grid to fulfill the energy demand. These distributed inverters will have the phase difference among their output voltages. This difference of voltage will affect the power quality of the net output voltage. In this case voltage source inverters (VSI) of all the grid connected resources need to be synchronized so that they may be connected to grid without causing any fault in the system. In this research a solution is presented to synchronize all DC/AC converters from different resources. Solution is supported by MATLAB simulations.**

Index Terms-- **Inverters; Synchronization; Voltage source inverters; DC/AC converter**

I. INTRODUCTION

The trend of using renewable energy rather than fossil fuels for generation of electricity has increased in recent times due to many reasons. One of the basic reasons is its low environmental impact. The raise in installation of renewable energy sources all over the world is basically motivated by economic and environmental factors. In addition to this due to drastic raise in population and increased consumption of energy, renewable energy resources are distributed in remote areas [1]. Numerous nations are progressively depending on sustainable power to move to a low-carbon economy [2]. These distributed energy generating units are not capable to fulfill the energy demand of locality as a standalone unit as compared to be used after integrating it with the Grid [3]. Renewable energy sources at low voltage (LV) and medium voltage (MV) levels are connected as a small-scale distributed generation (DG) unit via AC inverters. Since characteristics of inverters output are significantly different from other conventional electrical generators i.e., synchronous generators, so integration of inverters with the grid need some special attention [4]. This interconnectivity with the grid involves some extra equipment like inverters and converters. When a system is connected on electrical grid, there are mainly two types of configurations; “ON-grid” and “OFF-grid”. OFF-grid is those systems which are not connected to grid, and consumption of energy is of local nature [5] as shown in Fig. 1. These types of energy systems possess battery banks for storage of energy, which enable to supply energy even in case of absence of renewable energy driving force. But this configuration is not long lasting as it depends on the capacity of battery bank to store energy [6].

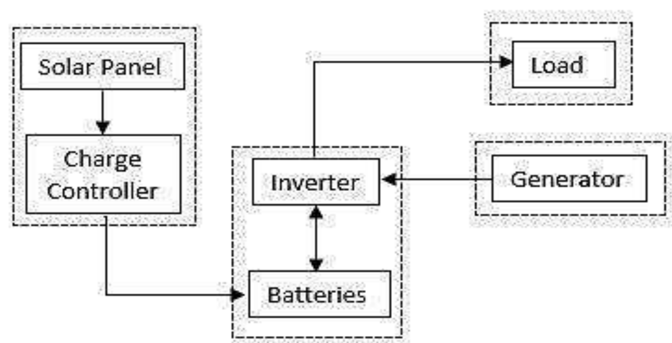

FIGURE 1: Schematic of OFF-Grid Inverter

ON-grid systems are those which contain the inverter connected to the grid and can supply energy to the grid after being controlled as a voltage supply or a current supply as shown in Fig. 2. It consists of a synchronization unit to synchronize with the grid along with adjacent distributed units. The interface which is used to connect with ON-GRID renewable energy mainly consists of voltage source inverter [7]. So, to make the generation of renewable resources completely synchronized with the grid, first of all, the inverters of distributed generation need to be synchronized. The synchronization unit needs to provide the frequency and the amplitude, in addition to the phase [8]. These issues are focused while defining synchronization mechanism by considering the renewable sources, storage elements, loads and generation units into a locally controllable system.

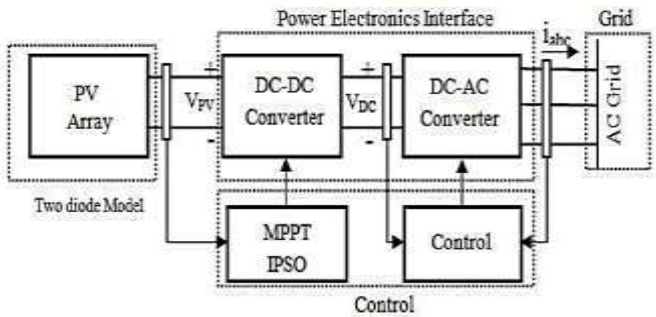

FIGURE 2: Schematic of ON-Grid Inverter.

When it comes to synchronization, main components in AC networks are grid-forming units [9]. These units are responsible for providing synchronized frequency and specified voltage levels in whole network. Grid forming units in conventional AC networks are Synchronous Generators. But when inverters are integrated with the grids, grid-forming functions are performed by inverter interfaced sources. And the inverters which operate in grid-forming mode can be ultimately represented as AC Voltage sources [10]. Primarily inverters can be synchronized with some external communication signal that will take one unit as a master and all other units will sync with it as slave units. Furthermore, for redundancy more than one unit can be set as masters units. So that when signal from one master unit is distorted, all slave units may sync with redundant master unit [6].

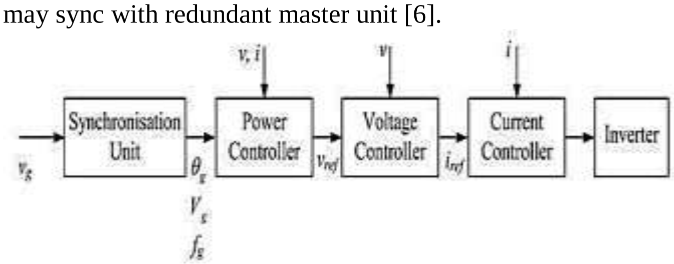

FIGURE 3: Controlled as Voltage Supply

Concept of synchro-inverter also used previously in which Phase Locked Loop (PLL) synchronization unit [11] is incorporated to provide the phase, frequency and amplitude from the connected grid as reference [12]. In this scenario control structure can be controlled as a voltage supply shown in Fig. 3 or current supply [13] shown in Fig. 4.

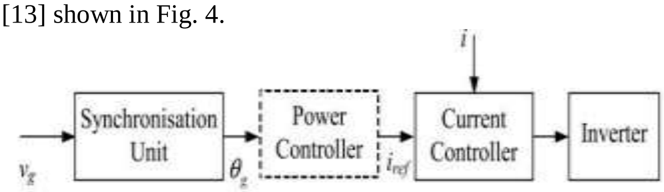

FIGURE 4: Controlled as Current Supply

Other ways can also be adopted to get synchronization done. So, it is explained in this paper that there is no necessity of any explicit signal for synchronization as the network frequency serves as an implicit common communication signal. The main Contribution of this paper is as follows: 1) As a result of past conversation we focused on the synchronization among inverters prior synchronizing them with grid. 2) Unlike conventional technique of synchronization In AC networks, our work elaborated the use of implicit communication signal [14] for synchronization i.e., network frequency as a standard signal of synchronization. We also provide protection mechanism to avoid any intrusion or distortion in synchronization signal. Outline of this paper is as follows. In the beginning we introduce the concept and importance of Renewable resources to generate electricity. Section I includes all the progress so far on ON-GRID inverters synchronization. In Section II we have elaborated our work and comprises over the mathematical model of inverter and its control unit. Section III contains simulation results of proposed model. In section IV conclusion and scope of future work are given

II. MATHEMATICAL MODELING

Mathematical modeling is basically used to get detailed insight of theoretical and numerical problems. A better insight of aforesaid problems can be get using mathematical modeling. It is quite useful in defining a proper application. Analytical model is basic tool to predict performance, limits stability and stats by considering different system parameters and by using different control laws. Mathematical model must be established before entering into design phase of system. Considering all the required parameters, mathematic model is devised after taking into account a three-phase inverter. Details of switching state functions are also considered and explained in detail.

A. THREE PHASE INVERTER

Typical configuration of 3-Phase full bridge inverter is shown in Fig. 5. When switching frequency is set properly and high enough then this PWM inverter can be taken as voltage source inverter VSI. SPWM Techniques are applied to get proper sinusoidal output waveform from the inverter with minimal undesired harmonics [15],[16],[17],[18],[19-22].

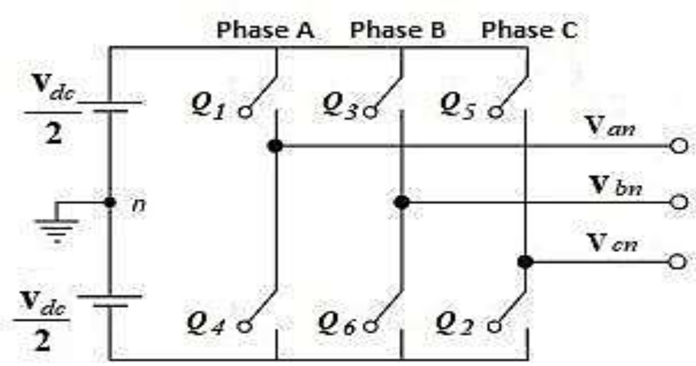

FIGURE 5: 3-Phase Inverter Model

Control signal is provided by PWM to control six semiconductor switching devices (Q1 to Q6) to get sinusoidal three phase AC voltage with required frequency and magnitude at the inverter output. The operation of three-phase inverter is divided in 8 modes as shown below. Each switch state is shown in every mode. Table-I shows detailed description for inverter phase and line voltages.

TABLE I: Reference frame dq voltage

Mode	Vq	Vd	Vo
A	0	0	$\frac{V_{dc}}{2}$
B	$\frac{V_{dc}}{3}$	$\frac{-V_{dc}}{\sqrt{3}}$	$\frac{V_{dc}}{6}$
C	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{\sqrt{3}}$	$\frac{V_{dc}}{6}$
D	$\frac{2V_{dc}}{3}$	0	$\frac{-V_{dc}}{6}$
E	$\frac{-2V_{dc}}{3}$	0	$\frac{-V_{dc}}{6}$
F	$\frac{-V_{dc}}{3}$	$\frac{-V_{dc}}{\sqrt{3}}$	$\frac{-V_{dc}}{6}$
G	$\frac{-V_{dc}}{3}$	$\frac{V_{dc}}{\sqrt{3}}$	$\frac{-V_{dc}}{6}$
H	0	0	$\frac{V_{dc}}{2}$

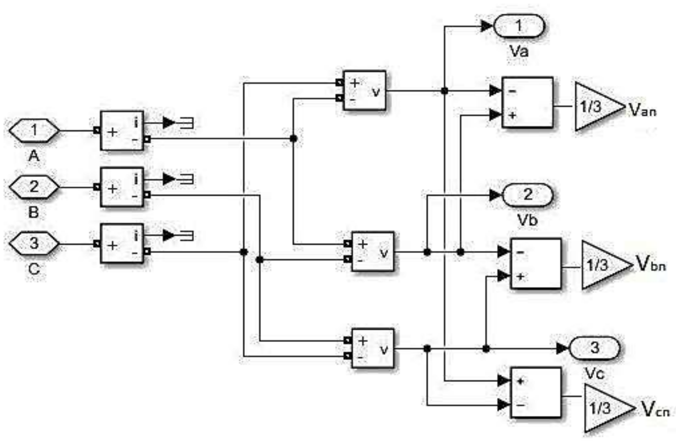

FIGURE 6: Switching state function for inverter line and phase voltages

Mathematically switching functions can be described as follows. Line output voltages of PWM inverter are calculated by switching state functions of three phase inverter as described by the help of Fig. 6. Three-phase switching state functions S_a, S_b and S_c of the inverter are used to calculate the output voltages at output of PWM Inverter.

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} U_{dc} \qquad (1)$$

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (2)$$

Mathematically switching functions can be expressed as follows

$$S_a(\omega t) = \sum_{k=1,3,5\ldots}^{\infty} A_k \sin k\omega t$$

$$S_b(\omega t) = \sum_{k=1,3,5\ldots}^{\infty} A_k \sin k(\omega t - \tfrac{2\pi}{3}) \qquad (3)$$

$$S_c(\omega t) = \sum_{k=1,3,5\ldots}^{\infty} A_k \sin k(\omega t - \tfrac{4\pi}{3})$$

By putting values of switching function in equation (2), we get the values of S_a, S_b and S_c as follows.

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_1} \\ \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_2} \\ \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_3} \end{bmatrix} U_{dc} \quad (4)$$

Finally, by putting all values in (1).

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_1} \\ \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_2} \\ \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_3} \end{bmatrix} U_{dc} \quad (5)$$

Similarly, we can get same equations for inverter 2

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_1} \\ \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_2} \\ \sum_{\infty}^{\infty} k = 1,3,5..^{A_k \sin k\emptyset_3} \end{bmatrix} U_{dc} \quad (6)$$

Where the values of phi in above equation are as follows

$$\emptyset_1 = 2\pi \frac{1}{T_1}(\frac{1}{T_1} = K_1)$$

$$\emptyset_2 = 2\pi \frac{1}{T_2}(\frac{1}{T_2} = K_2)$$

$$\emptyset_3 = 2\pi \frac{1}{T_3}(\frac{1}{T_3} = K_3) \qquad (7)$$

III. CALCULATIONS AND DERIVATIONS

On the basis of switching functions of both inverters under consideration, following equations can be derived to figure out the required adaptation law.

$$U_{AB} = \frac{1}{2}\ (S_a - S_b)\ \rightarrow\ U_{A_1B_1} = \frac{1}{2}\ (S_{a_1} - S_{b_1})$$

$$U_{BC} = \frac{1}{2}\ (S_b - S_c)\ \rightarrow\ U_{B_1C_1} = \frac{1}{2}\ (S_{b_1} - S_{c_1})$$

$$U_{AC} = \frac{1}{2}\ (S_a - S_c)\ \rightarrow\ U_{A_1C_1} = \frac{1}{2}\ (S_{a_1} - S_{c_1}) \quad (8)$$

When both inverters will be interconnected, then definitely there will be some difference in the waveforms of both inverters. This difference will be the error and can be

$$U_{AB_1} = \frac{1}{2}\ [(S_a - S_b) - (S_{a_1} - S_{b_1})]$$

$$U_{AB_1} = \frac{1}{2}\ [(S_a - S_{a_1}) - (S_b - S_{b_1})]$$

$$U_{BC_1} = \frac{1}{2}\ [(S_b - S_{b_1}) - (S_c - S_{c_1})]$$

$$U_{CA_1} = \frac{1}{2}\ [(S_c - S_{c_1}) - (S_a - S_{a_1})] \quad (9)$$

Where the values of switching functions in error calculation can be given as

$$S_a(\omega t)\ =\ \sum_{\mathrm{k}=1,3,5\ldots}^{\infty}\ [A_k \sin(k\omega\mathrm{t} + \emptyset_a)]$$

$$S_{a_1}(\omega t)\ =\ \sum_{\mathrm{k}=1,3,5\ldots}^{\infty}\ [A_k \sin(k\omega\mathrm{t} + \emptyset_{a_1})]$$

$$S_b(\omega t)\ =\ \sum_{\mathrm{k}=1,3,5\ldots}^{\infty}\ [A_k \sin(k\omega\mathrm{t} + \emptyset_b)] \quad (10)$$

$$S_{b_1}(\omega t)\ =\ \sum_{\mathrm{k}=1,3,5\ldots}^{\infty}\ [A_k \sin(k\omega\mathrm{t} + \emptyset_{b_1})]$$

$$S_c(\omega t)\ =\ \sum_{\mathrm{k}=1,3,5\ldots}^{\infty}\ [A_k \sin(k\omega\mathrm{t} + \emptyset_c)]$$

$$S_{c_1}(\omega t)\ =\ \sum_{\mathrm{k}=1,3,5\ldots}^{\infty}\ [A_k \sin(k\omega\mathrm{t} + \emptyset_{c_1})]$$

Now, Taking

$$X = \frac{1}{2}\sum_{\mathrm{k}=1,3,5\ldots}^{\infty} A_k$$

$$U_{AB_1} = X[\sin(k\omega\mathrm{t} + \emptyset_a) - \sin(k\omega\mathrm{t} + \emptyset_{a_1})]$$

$$U_{AB_1} = X[2\cos\left(k\omega\mathrm{t} + \frac{\emptyset_a + \emptyset_{a_1}}{2}\right) - \sin\left(k\omega\mathrm{t} + \frac{\emptyset_a - \emptyset_{a_1}}{2}\right)]$$

$$U_{BC_1} = X[\sin(k\omega\mathrm{t} + \emptyset_b) - \sin(k\omega\mathrm{t} + \emptyset_{b_1})]$$

$$\boldsymbol{U_{BC_1} = X\left[2\cos\left(k\omega\mathrm{t} + \frac{\emptyset_b + \emptyset_{b_1}}{2}\right) - \sin\left(k\omega\mathrm{t} + \frac{\emptyset_b - \emptyset_{b_1}}{2}\right)\right]}$$

$$U_{BC_1} = X\left[2\cos\left(k\omega\mathrm{t} + \frac{\emptyset_b + \emptyset_{b_1}}{2}\right) - \sin\left(k\omega\mathrm{t} + \frac{\emptyset_b - \emptyset_{b_1}}{2}\right)\right] \quad (10)$$

$$U_{CA_1} = X[\sin(k\omega\mathrm{t} + \emptyset_c) - \sin(k\omega\mathrm{t} + \emptyset_{c_1})]$$

$$U_{CA_1} = X\left[2\cos\left(k\omega\mathrm{t} + \frac{\emptyset_c + \emptyset_{c_1}}{2}\right) - \sin\left(k\omega\mathrm{t} + \frac{\emptyset_c - \emptyset_{c_1}}{2}\right)\right]$$

Here some assumptions are made to derive the adaptation law:

$$\emptyset_a = \omega T_{(t)}$$

$$\emptyset_{a_1} = \omega T_{(t)}$$

$$\delta_{(t)} = \frac{1}{2}(\emptyset_a - \emptyset_{a_1})$$

$$\dot{\delta}_{(t)} = -\frac{1}{2}\emptyset_{a_1}$$

$$\dot{\emptyset}_{a_{1(t)}} = -2\delta(t)$$

IV. SIMULATION

Simulations are performed and results are shown in Fig. 7 and Fig. 8. In Fig. 7 output of two inverters is shown when they are working without any synchronized unit. It is obvious from the waveform that all three phases of both inverters are not synchronized.

When control is applied to both inverters in order to make output of both inverters synchronized, following output is received. Figure 8 shows how the synchronization makes all three phases of both inverters to get sync with main control signal.

V. CONCLUSIONS

We have proposed a solution to synchronize distributed inverters of renewable energy resources using implicit communication signal i.e., frequency of that network to which all inverters will be connected ultimately, opposed to previously used explicit signals i.e., GPS based synchronizing signals. Results are supported and demonstrated in simulations where two distributed sources were considered at a time.

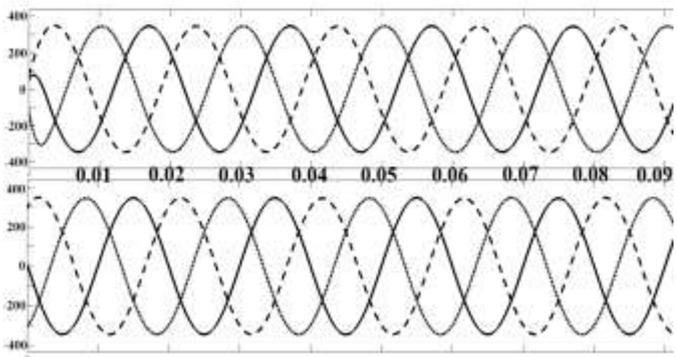

FIGURE 7: Output of inverters without applying control

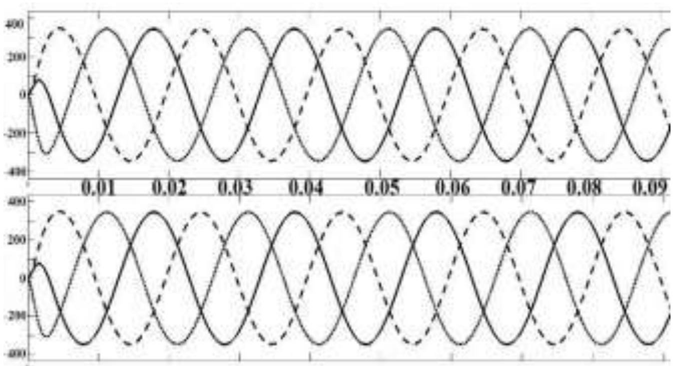

FIGURE 8: Synchronized output of inverters after applying control

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