Fuzzy Based Grid Synchronization Method for Distributed Energy Resource Converters

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Abstract—Nowadays, renewable energy resources such as solar Photo voltaic (PV) cells, fuel cells (FC) and wind turbines(WT) plays an important role in generating electricity nearer to local loads that are integrated to utility grid. For integration of distributed energy resource converters to utility grid, a synchronization i.e matching of frequency, phase, amplitude of output voltages, active power and reactive power must exist in between output of distributed energy resource converters and utility grid. The main objective of this paper is to maintain synchronism between the output of distributed energy resource converter with utility grid. In this paper a fuzzy based grid synchronization method is proposed to achieve the synchronization. The proposed method is modeled and simulated in MATLAB/SIMULINK Software.

Keywords—Distributed Generation Systems (DGSs), Grid Synchronization, Microgrid, Fuzzy Logic Controller.

I. INTRODUCTION

Nowadays, renewable energy sources (RES) or Distributed Energy Resources (DERs) play an important role for generating electricity in world-wide economy. Distributed Generation (DG) also known as small-scale (typically 1KW-50 MW) electric power generators used to produce electricity nearer to the location of customers that are tied to a microgrid. Renewable energy resources such as solar photo voltaic, wind turbines and fuel cells are used for distributed generation. Distributed generation enhances the reliability of power supply. The capital cost of distributed generation system is usually low based on its size as explained in [1].

A microgrid is a part of distribution network that includes multiple loads and distributed energy resource converters that are operated in parallel with the boarder utility grid [2]-[5]. It helps in integration of distributed energy resource converters to microgrid. Microgrid is a part of distributed generation system. It is a localized grouping of electricity generation, energy storage and loads that normally operates connected to a traditional centralized utility grid. The components of microgrid involves distributed generation resources such as photovoltaic panels, small wind turbines, fuel cells, etc.

The storage devices are batteries, super capacitors, flywheel etc along with local loads. Better efficiency, superior quality with high reliability of power supply having environmental as well as economical benefits can be achieved by using microgrid. A droop control is a control technique applied to distributed generation system for primary frequency control and as well as voltage control for load sharing between local loads to utility Grid.

By controlling the frequency, as well as voltage, corresponding active power (P) and reactive power (Q) can be controlled in distributed generation. Increase in active power output results in reduction of frequency and the corresponding increase in the reactive power results in decrease of voltage as explained in [6].

The concept of Phase Locked Loop (PLL) is used for the implementation of grid synchronization method. PLL is used for the estimation of grid voltage, phase angle and frequency. A PLL is a control system in which output signal is generated by relating its phase to the phase of an input signal. A PLL can track an input frequency or it can generate a frequency that is a multiple of the input frequency as explained in [7]-[10].

This paper a fuzzy logic controller based synchronization method is proposed for achieving the grid synchronization in terms of frequency, phase angle, amplitude of output voltages, active power and reactive power in between converter output and Distributed Energy Resource Converters (DERCs). The fuzzy logic controller is replaced by proportional integral (PI) controller for obtaining fast dynamic response, low steady error and for stable operation of the grid as explained in [18]-[19].

II. OPERATION OF DISTRIBUTED ENERGY RESOURCE CONVERTERS

Fig.1 represents the proposed distributed generation system comprises of two Voltage Source Inverters (VSI) fed with a source with line impedances \( R_1 + jX_1 \), \( R_2 + jX_2 \) connected to utility grid by means of static switch. It involves a dynamic load with both active and reactive power components [11].
The static switch is open before synchronization that is in islanded mode of operation. By closing the static switch the distributed generation system is connected to utility grid based on the commands received from the secondary controller after the synchronization achieved in terms of frequency, phase, and amplitude of output voltages, active power and reactive power [16]-[17]. The distributed generation system structure is operated in two modes. They are Grid Connected (GC) mode and Islanded or Stand Alone (SA) mode. In Grid connected mode of operation, the utility grid is active and static switch is closed thereby distributed generation system is connected to utility grid after the grid synchronization is achieved. In Islanded mode of operation utility grid is inactive and it does not supplies power and static switch is open.

III. CONTROL OF DISTRIBUTED ENERGY RESOURCE CONVERTERS

The controllers [8] involved in distributed generation system structure are:

a) Primary controller or PLL controller:

The primary controller senses the difference voltage from the utility grid voltage and point of common coupling voltage. A phase locked loop block is used in the primary controller to generate the input frequency signals from the primary controller. A phase locked loop is a control loop which generates an output signal by comparing its phase to the phase of an input signal. By maintaining the input and output frequencies lock step also implies keeping the input and output frequencies the same. It can also senses a frequency, in addition of synchronizing the signals [7].

A phase detector relates the reference input to the feedback input and generates an error signal. The error signal is then passed through a loop filter for harmonic elimination which is fed to the voltage controlled oscillator that helps in generating a periodic frequency output from the given input reference signal.

The Primary Controller generates the phase angle difference by passing the output frequency signals from the PLL to the integrator. The differential voltage is obtained by the taking the difference of grid voltage and the point of common coupling voltage. The differential phase angle difference can be obtained by taking the difference between the Grid phase angle and Point of Common Coupling (PCC) phase angle.
Parks transformations are involved in conversion of voltages from three phase to two phase \((abc - dq)\).

The mathematical modeling that involves in primary controller for generating the difference voltage and phase angle difference is:

\[ V_d = V_G - V_{PCC} \]  \(1\)

Where,
\[ V_d \] = Difference voltage
\[ V_G \] = Grid voltage
\[ V_{PCC} \] = Point of common coupling Voltage

\[ \lambda_d = \lambda_G - \lambda_{PCC} \]  \(2\)

Where,
\[ \lambda_d \] = Phase angle difference
\[ \lambda_G \] = Phase angle of grid
\[ \lambda_{PCC} \] = Point of Common Coupling phase angle

**b) Secondary controller:**

The secondary controller is linked to the primary controller from where the operation mode signals such as phase angle difference \(\lambda_d, V_d\) differential voltage is taken from the primary controller. The secondary controller involves the sharing of active power as well as reactive power explained in [12]. The mathematical modeling involved in the secondary controller is [13]-[15].

Instantaneous active power,

\[ p = u_d i_d + u_q i_q \]  \(3\)

Where,
\[ p \] = Instantaneous active power
\[ u_d, u_q \] = Instantaneous voltages along d and q axes
\[ i_d, i_q \] = Instantaneous currents along d and q axes

and

Instantaneous reactive power,

\[ q = u_d i_d - u_q i_q \]  \(4\)

Where,
\[ q \] = Instantaneous reactive power
\[ u_d, u_q \] = Instantaneous voltages along d and q axes
\[ i_d, i_q \] = Instantaneous currents along d and q axes

The relationship between active power \((P)\) and frequency \((f)\) is expressed as:

\[ f = f_0 - k_p (p - p_0) \]  \(5\)

Where,
\[ f \] =System frequency
\[ f_0 \] = Base frequency
\[ k_p \] = Frequency droop control setting
\[ p \] =Active power of the unit
\[ p_0 \] = base active power of the unit

Similarly, the relationship between reactive power \((Q)\) and frequency \((f)\) is expressed as

\[ V = V_0 - k_q (Q - Q_0) \]  \(6\)

Where,
\[ V \] =voltage of the measurement location
\[ k_q \] = voltage droop control setting
\[ V_0 \] = base voltage
\[ Q \] = Reactive power of the unit
\[ Q_0 \] = Base reactive power of the unit.

The secondary controller contains the voltage (PI) Controller and current controller which helps in sensing the voltages and currents from that instantaneous active and reactive power can be calculated. The proportional sharing of the active and reactive power can be accomplished by the secondary controller by implementing the relationship between frequency as well as active power and voltage as well as reactive power. A fuzzy logic controller is used in secondary controller for obtaining fast dynamic response, low steady error and for stable operation of the grid instead of proportional integral controller (PI) controller.
IV. FUZZY LOGIC CONTROLLER

The concept on fuzzy set theory was introduced by L. A. Zadeh in 1965. Fuzzy Logic is rule based and it is application of human knowledge on system behavior as explained in [18]-[19]. Fig.3 represents the schematic diagram of fuzzy based system.

Fuzzy logic controller operation mainly involves the execution of four major operations:

- Fuzzification
- Rule based Inference system
- Composition and Defuzzification

Fuzzification involves the conversion of crisp values or classical set values to Fuzzy rule base values. It involves the choice of Variables, fuzzy Input and output variables and the evaluation of membership functions. It involves fuzzy subset rules, composition and defuzzification. For assigning each fuzzy subset rule based value to the output variable a Rule based fuzzy inference system is necessary. Composition helps in forming a Single fuzzy subset rule based Value assigned to an output variable from a multiple rule based fuzzy subset values.

Defuzzification helps in the conversion of composition of fuzzy rule based value to a single crisp value. A PI controller is replaced with a fuzzy controller as shown in fig.4.

The fuzzy logic controller helps in attaining the quick, stable response and in reducing the steady state error. The instantaneous current $I_{id}$ is compared with the reference current $I_{id}$ to generate the error signal which is fed to the fuzzy logic controller. The fuzzy logic generates the corresponding output based on the corresponding rule based system and membership functions.
A. Fuzzy logic rules:

The main objective of designing the Fuzzy logic rules is to synchronize the grid parameters such as grid frequency, phase angle, amplitude of output voltages, active power and reactive power with the output of the distributed energy resource converters. The error and change of error are the inputs of the fuzzy logic controller. The corresponding error and change of error are divided into seven groups. The rules of fuzzy logic controller are shown in below Table 1.

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Where,

NH: Negative High
NM: Negative Medium
NS: Negative Small
ZE: Zero
PH: Positive High
PM: Positive Medium
PS: Positive Small

The fuzzy logic controller block diagram as shown fig.8. In this simulink model the Proportional Integral controller (PI) is replaced by fuzzy logic controller. The fuzzy logic controller generates the corresponding desired output by using the fuzzy rule based values and with the corresponding membership functions as already mentioned.

V. SIMULATION RESULTS

Fig.6 represents the simulink model of the proposed DG System with utility grid.
Fig 6: Simulink model of the proposed DG system.

Fig 7: Simulink model of primary controller
Fig 9: Simulink Model of Fuzzy based controller

Fig. 10: Inverter 1 voltages

Fig 11: Inverter 2 voltages

Fig 10: Inverter 1 voltages \( V_a, V_b, V_c \)

Fig 11: Inverter 2 voltages \( V_a^1, V_b^1, V_c^1 \)
Case 1:

![Graph of grid angular frequency Vs time](image1)

(a) With existed PI controller  
(b) with fuzzy controller

Fig 12: waveforms of grid angular frequency (rad/s) Vs time (secs) : (a) with existed PI controller (b) Proposed fuzzy system

Case 2:

![Graph of PCC angular frequency Vs time](image2)

(a) with existed PI controller  
(b) with fuzzy controller

Fig 13: waveforms of PCC angular frequency (rad/s) Vs time (secs) : (a) with existed PI controller  
(b) Proposed fuzzy controller
Case 3: Figure 14 (a) & (b) represents the voltage magnitude difference that varies with respect to the time period for existed PI controller and fuzzy controller respectively. The waveform varies smoothly after 40s and it rises sharply at the instant of 15s.

Case 4: Figure 15 (a) & (b) represents the active powers $P_1$ & $P_2$ with respect to the time period for fuzzy controller and existed PI controller respectively. The active power $P_1$ is started from 200W and the active power $P_2$ is started from 400W.
**Case 5:** Figure 16 represents the Reactive powers \( Q_1 \) & \( Q_2 \) with respect to the time period for fuzzy controller and existed PI controller respectively. The Reactive powers \( Q_1 \), \( Q_2 \) starts from 105 VAR and 116 VAR.

![Figure 16: waveforms of Reactive powers \( Q_1 \) & \( Q_2 \) (VAR) Vs time (secs): (a) Proposed fuzzy controller (b) with existed PI controller]

**Case 6:** Figure 17 represents the Voltage that varies with respect to the time period for fuzzy controller and the existed PI Controller respectively. The Voltage starts from 210V which rises exponential with respect to time period.

![Figure 17: waveforms of Voltage [volts] Vs time (secs): (a) Proposed fuzzy controller (b) with existed PI controller]
Case 7: Figure 18 represents the Angular difference that decays exponentially starting from 0.35 radians and obtains a smooth response after 40s.

![Waveform Graph](image1)

(a) with proposed fuzzy controller  
(b) with existed PI controller

Fig 18: Waveforms of Angular difference (rad) Vs time(secs):(a) Proposed Fuzzy controller, (b) with existed PI controller

Case 8: Figure 19 represents the Angular frequency that varies with respect to time period. Sudden decrease in the operating frequencies, helps to match the PCC voltage phase angle with the grid voltage phase angle.

![Waveform Graph](image2)

(a) with Proposed fuzzy controller  
(b) with existed PI controller

Fig 19: Waveforms of Angular frequency (rad/sec) Vs time(secs): (a) Proposed fuzzy controller (b) with existed PI controller.

VI. CONCLUSION

A fuzzy logic based secondary controller is used for achieving the grid synchronization by integrating the distributed energy resource converters to microgrid. The simulation results with fuzzy logic controller helps in obtaining the quick response, low steady state error and reduces the harmonics with low ripple content.

The power factor is also improved near PCC and power quality has been increased by the influence of multiple types of DG sources in distribution generation system. Hence, the proposed fuzzy logic system has better performance for achieving grid synchronization than existed conventional PI controller.
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