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Grid Synchronization Techniques and Analysis in Distributed Power Generation Systems under Unbalanced Conditions

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Abstract – The grid connected Distributed Power Generation Systems (DPGS) experiences more sensitive behaviour against small variations occurs in grid parameters. The variations or unbalance in grid parameters are mainly due to the presence of voltage sags, frequency variations, and distorting harmonics in the grid. The adverse effect of unbalanced grid conditions may create the failure in synchronized operation between DPGS and its connected grid.In this work to provide continuous synchronization for DPGS during both balanced and unbalanced condition of grid, two novel grid synchronization techniques based on Phase Locked Loop (PLL) studied are (i) Modified Double Decoupled Synchronized Reference Frame PLL (ii) Modified Double Second Order generalize integrator PLL.

The main aim of the presented modules is to provide sequence components of grid voltage. These sequence components helps in determining magnitude and phase angle of unbalanced grid. The presented PLL configurations are worked based on synchronous reference frame algorithms i.e. the Park's conversion method is applied to convert 3-phase ABC voltage vector to rotating d-q reference frame components. The generated positive sequence d-component is used to determine magnitude of utility voltage and the positive sequence q-component is used to get phase angle of grid voltage using Phase Locked Loop (PLL) circuit. The PLL circuit also maintains the frequency and phase angle of DPGS same as the determined new phase angle value of grid voltage.

The equivalent simulation circuit of each module is developed using MATLAB Simulink. Thesimulation of each module is carried out by creating different unbalanced conditions of grid. From the simulation results it can be observe that the generated positive sequence d- component provides the magnitude of grid voltage accurately during both balanced and unbalanced conditions. Similarly the determined positive sequence q-component is utilized by Phase Locked Loop circuit for providing phase angle plot of grid voltage accurately. The time required for each module in determining phase angle and magnitude of grid voltage after creating faultis within 20-25ms i.e. within two cycles of faulted voltage. The presented techniques are also tested to observe their response in the presence of harmonic distortions. In all grid unbalanced conditions both techniques provide satisfactory results with free of harmonics.

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INTRODUCTION

The power generation from renewable sources is presently reached 25 to 30% of total generated power. Among all renewable power systems, wind and photovoltaic are remarkable models. But the increased installation of these systems in the network may require increased grid stability and low voltage ride through (LVRT). LVRT defines the constraints which essential to determine the fault limits, maintains needed voltage profile and made the generation system remains connected to the grid network i.e. maintains synchronization under grid unbalances like voltage dips.

Synchronization is the term describes, process of maintaining identical waveform, frequency, voltage and phase angle of a source with its interconnected power system within the acceptable limit, this is required to have a parallel operation between them. Perfect synchronization offers the following outcomes such as;

1) Two parallel connected systems have minimum Disturbances.

2) Oncoming generator experience acceptable shock.

3) Equipment survives long time.

4) Fast generator loading helps in supplying energy to loads quickly. [1]

Effects of synchronization failure are given by

- Reverse flow of power i.e. from existing power system to source. This may damage the generator windings and also generator may acts as motor.
- Loss of load of the source
- Loss of protected equipment's, meters, etc. due to the reverse power flow.
- Large disturbance experienced by parallel systems etc.

These effects can be avoided or minimized by maintaining continuous synchronization between parallel systems, by using some advanced synchronizing techniques like zero crossing detector and phase locked loop based algorithms.

This paper mainly consider distributed generation in the discussion of synchronization issue, however it is essential to maintain synchronization in all generation power plant but the renewable DG(Distributed Generation) systems are more sensitive towards the unbalanced conditions. The Wind Turbine constructed with Squirrel-Cage Induction Generator (WT-SCIG), and some power converters used in solar power generation are very sensitive when sudden voltage dip occurs [2].

In this work, upgraded and advanced grid synchronization techniques are going to be studied and analysed are the Modified Double Decoupled Synchronous Reference-Frame PLL (MDDSRF PLL) and the Modified Double Second Order Generalized Integrator PLL (MDSOGI PLL).

The main work of each model is to determine the positive sequence components of grid voltage during grid unbalances. These positive sequence components have the information of phase angle and magnitude of unbalanced grid voltage. The information of magnitude and phase angle data of unbalanced grid voltage helps in adjusting the grid side converter output of DPGS same as the connected grid. Hence DPGS is said to be maintain its synchronized operation with connecting grid during unbalanced conditions also.

The MDDSRF and MDSOGI PLL are the modified versions of basic SRF PLL. The operating principle of basic SRF PLL is determining positive sequence components of grid voltage in terms of synchronously rotating d-q components using Park's and Clark's conversions. The response of SRF PLL is satisfactory only in balanced condition of utility. During unbalanced conditions of grid, the result of SRF PLL contains second order harmonics in its determined positive sequence d-q components.

To overcome the demerits of SRF PLL, decoupling networks are introduced in MDDSRF PLL. The decoupling network helps for cancel out the second order harmonics and provides the accurate positive sequence d-q components. Similarly in MDSOGI PLL the second-order generalized integrator type signal generator (SOGI) is used for generating in-phase and quadrature signals in terms of α-β reference frame.The SOGI itself acts as a band pass filter which helps in rejecting harmonic components in a utility voltage. Therefore the output of SOGI is accurate and free of harmonics and is directly used for converting them into synchronously rotating d-q positive sequence components.

In this paper the performance and reliability of each algorithm in detection of amplitude and phase angle of positive sequence component of grid voltage under unbalanced and distorted situations aregoing to be evaluated. The simulation of both techniques are carried out using MATLAB Simulink and the results of each model was analyzed by considering different unbalanced conditions like voltage sags and harmonic distortions.

II. GRID SYNCHRONIZATION OF DPGS USING MODIFIED DOUBLE DECOUPLED SRF PLL

The MDDSRF PLL was established for upgrading the basic SRF PLL. This synchronization arrangement has 2-SRFs rotating withessential utility frequency, (i) clockwise and(ii) counter-clockwise to get perfect judgment of the +ve and -ve sequence elements of the grid voltage during unbalanced grid faults. The illustration of the MDDSRF PLL is presented in Fig.1

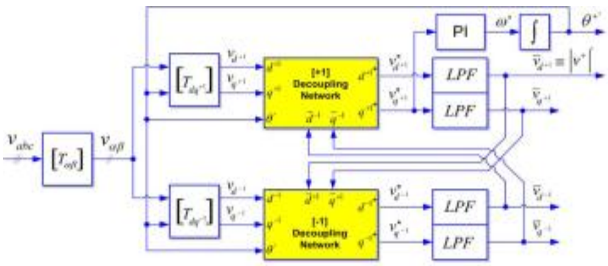

Fig.1 MDDSRF-PLL block diagram.

When the 3-phase grid voltage is going to be distorted or unbalanced due to fault, the essential +ve sequence voltage will cause dc voltage on dq^{+1} axes of the +ve sequence SRF and ac voltages with double the essential utility frequency on $dq^{-}1$ axes of –ve sequence SRF. Similarly, thevector of -ve sequence voltage seems as dc-component on –ve sequence SRF and an ac signal with double fundamental frequency on +ve sequence SRF. Here the magnitude of the ac-oscillation on the+ve sequence SRF equalsto the dc-level on -ve sequence SRF and vice-versa. The application of decoupling network helps tocancel out the ac voltage signals. The Low-pass filter (LPFs) in Fig 1 is accountable for getting the pure dc element from theoutput of decouple network.

The finally obtained dc components provide the amplitude and phase angle of the unbalanced utility. Here the PI controller helps in finding phase angle of grid by utilizing decoupled positive sequence q-axis component. The magnitude can be directly obtained from decoupled positive sequence d-axis component of grid unbalanced voltage.

III. THE MATHEMATICAL ANALYSIS OF MDDSRF PLL

During unbalanced utility circumstances, the voltage of the phase a, b, c can be expressed as

$$v_{usi} = V_{us}^{+1}\cos(\omega_u t) + V_{us}^{-1}\cos\left(-\omega_u t - \frac{2\pi}{3} + \emptyset^{-1}\right) + V_{us}^{0}\cos(\omega_u t + \emptyset^{0}) \quad (1)$$

Here the superscript notations like +1, -1 and 0 are used in above equation are described the the positive, -ve and zero sequence-components, in each case i = phases a, b, c and ϕ is change in phase angle. Using Clarke conversion, grid voltage in terms of αβ vector is expressed as,

$$v_{us\alpha\beta\gamma} = \begin{bmatrix} V_{us_\alpha} \\ V_{us_\beta} \\ V_{us_\gamma} \end{bmatrix}^T = [T_{u\alpha\beta\gamma}] \begin{bmatrix} V_{us_a} \\ V_{us_b} \\ V_{us_c} \end{bmatrix} \quad (2)$$

$$[T_{u\alpha\beta\gamma}] = \frac{2}{3}\begin{bmatrix} 1 & (-\frac{1}{2}) & (-\frac{1}{2}) \\ 0 & (\frac{\sqrt{3}}{2}) & (\frac{\sqrt{3}}{2}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3)$$

The vector of voltage on the αβ plane is (Neglecting zero-sequence component),

$$Vsu_{(\alpha\beta\gamma)} = \begin{bmatrix} V_{u_\alpha} \\ V_{us_\beta} \end{bmatrix} = V_{S(\alpha\beta)}^{+1} + V_{S(\alpha\beta)}^{-1}$$

$$= V_{us}^{+1}\begin{bmatrix} \cos(\omega_u t) \\ \sin(\omega_u t) \end{bmatrix} + V_{us}^{-1}\begin{bmatrix} \cos(-\omega_u t + \emptyset^{-1}) \\ \sin(-\omega_u t + \emptyset^{-1}) \end{bmatrix} \quad (4)$$

Here it is shown that input voltage involves of two sub vectors: V_{us}^{+1} and V_{us}^{-1},rotating with +ve angular frequency ω_u and rotating with -ve angular frequency $-\omega_u$ respectively.

The conversion of abc to αβ then to d-q with the help of referring fig 2 it can be drawn by the angular rotation of different stationary and rotating reference frame.

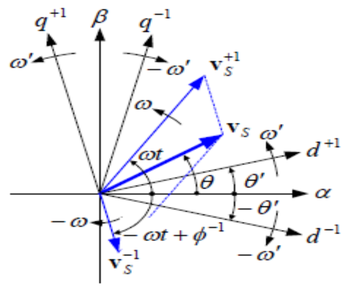

Fig 2: Voltage vectors based on reference frames of SRF

$$V_{us_{dq^{+1}}} = \begin{bmatrix} V_{usd^{+1}} \\ V_{usq^{+1}} \end{bmatrix} = [T_{udq^{+1}}]V_{us_{\alpha\beta}}$$

$$= V_{us}^{+1}\begin{bmatrix} \cos(\omega_u t - \theta') \\ \sin(\omega_u t - \theta') \end{bmatrix} + V_{us}^{-1}\begin{bmatrix} \cos(-\omega_u t + \emptyset^{-1} - \theta') \\ \sin(-\omega_u t + \emptyset^{-1} - \theta') \end{bmatrix} \quad (5)$$

$$V_{us_{dq^{-1}}} = \begin{bmatrix} V_{usd^{-1}} \\ V_{usq^{-1}} \end{bmatrix} = [T_{udq^{-1}}]V_{us_{\alpha\beta}}$$

$$= V_{us}^{+1}\begin{bmatrix} \cos(\omega_u t + \theta') \\ \sin(\omega_u t + \theta') \end{bmatrix} + V_{us}^{-1}\begin{bmatrix} \cos(-\omega_u t + \emptyset^{-1} + \theta') \\ \sin(-\omega_u t + \emptyset^{-1} + \theta') \end{bmatrix} \quad (6)$$

$$[T_{u(dq^{+1})}] = [T_{u(dq^{-1})}] = \begin{bmatrix} \cos(\theta') & \sin(\theta') \\ -\sin(\theta') & \cos(\theta') \end{bmatrix}$$

The PLL arrangement, similar to shown in Fig 1, regulating accurately its control constraints, to achieve θ' $=\omega_u$t.By using small signal analyses,the selection of control constraints for PLL are presented as assumptions of sin (ω_ut −θ′) = (ω_ut −θ′), cos (ω_ut −θ′) =1 and (−ω_ut −θ ′)=−2$\omega_u$tusing this assumed conditions, (5 &6) can be expressed as:

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$$V_{us_{(dq+1)}} = V_{us}^{+1}\begin{bmatrix}1\\ \omega_u t - \theta'\end{bmatrix} + V_{us}^{-1}\begin{bmatrix}cos(-2\omega_u t + \emptyset^{-1})\\ sin(-2\omega_u t + \emptyset^{-1})\end{bmatrix} \quad (7)$$

$$V_{us_{(dq-1)}} = V_{us}^{+1}\begin{bmatrix}cos(2\omega_u t)\\ sin(2\omega_u t)\end{bmatrix} + V_{us}^{-1}\begin{bmatrix}cos(\emptyset^{-1})\\ sin(\emptyset^{-1})\end{bmatrix} \quad (8)$$

Equation 7&8 consists of the constant values correspond to the amplitude of V_S^{+1} and V_S^{-1} in the dq^{+1} and the dq^{-1} axes respectively, and ac oscillating signals with 2 ω_u frequency with opposite rotation direction. This generated 2^{ω_u} ac signals can be attenuated by using Low pass filter but its dynamic response during unbalanced condition is very poor. Hence the decoupling network is introduced to cancel out the generated ac signals.

IV. SIMULATION OF MDDSRF PLL

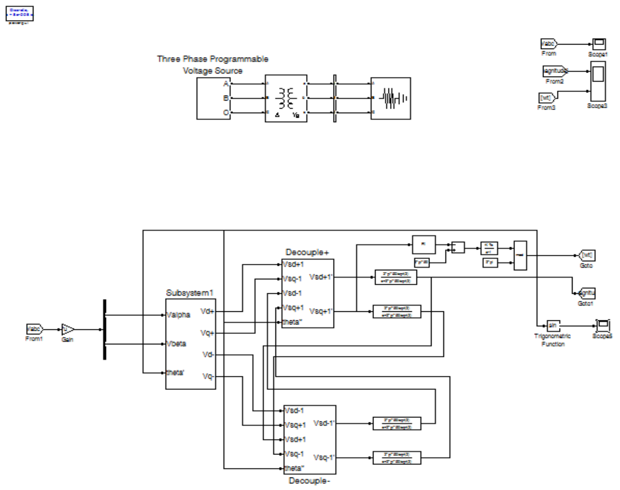


Fig 3: simulation diagram of MDDSRF PLL

Working

Initialy circuit is allowed to operate in balanced condition i.e. by generating balanced three phase supply upto 1sec. Then source voltage is provided to circuit with sags in the phase voltages based on the type of fault after 1sec. The detection of phase angle is continous for both balanced and unbalanced conditions. In balanced condition, error occure in phase angle is zero, because the reference voltage and source voltage both are having same magnitude and phase angle. During unbalance in utility their may be variations occure in amplitude, frequency and phase angle; this may cause synchronization failure between source and utility network. Hence to maintain synchronization during grid unbalances, the control of grid connected power converters of DGS is necessary and this is directly depends on estimation of amplitude and phase angle of possitive sequence voltage componet at fundamental frequency.

The MDDSRF PLL simulation describes the detection of positive and negative sequence component of unbalanced voltage hence the outputs of decoupling network i.e positive sequence direct axis component is used for amplitude detection and positive sequence quadrature axes component is used for detection of phase angle. Low pass filters are used for removing harmonics in sequence components.

V. GRID SYNCHRONIZATION OF DPGS USING MDSOGI-PLL

The MDSOGIPLL is one of the important modifications in the SRF PLL. MDSOGI PLL works with α-β stationary reference frame to get instant symmetrical elements (ISE) of utility network voltage. But ISE method requires two sets of signals namely, filtered versions of regular Vuα and Vuβ signals (derived from utility voltage (Vu) with abc as phases) and another filtered version set with derived by 90° phase shift of regularVuα and Vuβ signals.These filter versioned components of regular Vuα and Vuβ and its quadrature elements are generated by using two second order generalized integrators (SOGI). The SOGI acts as a band pass filter which helps in rejecting harmonic components in a utility voltage. The final filtered outputs of the two SOGI are $V'_{u\alpha}$ and $V'_{u\beta}$ and $qV'_{u\alpha}$ and $qV'_{u\beta}$. These components are used as an input to the block of positive sequence calculator (PSC) as described in fig 4.

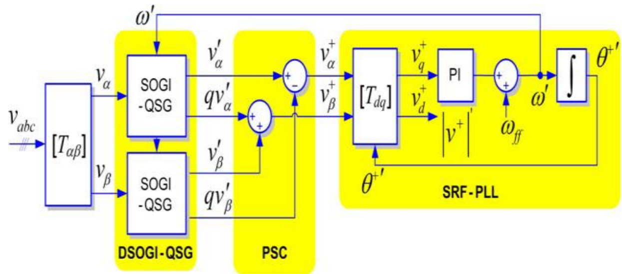


Fig. 4 MDSOGI-PLL.

After finding +ve phase-sequence in terms of αβ, the remaining process of finding of phase angle and magnitude of utility voltage is same as carried out in MDDSRF PLL i.e. by converting $V_{u\alpha}^{+}$ and $V_{u\beta}^{+}$ to V_{ud}^{+} & V_{uq}^{+}. Now the d-component of positive sequence (V_{ud}^{+}) is used to determine magnitude of utility voltage and the q-component (V_{uq}^{+}) is used to determine angular frequency (w'_u) using PI controller and phase angle (θ'_u) using integrator. The determined value of new angular frequency of utility voltage is taken as feedback to provide the center frequency (w'_u) to two SOGI systems.

VI. MATHEMATICAL ANALYSIS OF MDSOGI PLL

The instant symmetrical positive sequence elements of utility signals using αβ-reference frame is described in this section. Here the utility voltage (Vuabc) signals are converted into their +ve sequence elements and mathematically expressed as

$$v_{u_{abc}} = [v_{ua} \quad v_{ub} \quad v_{uc}]^T \qquad (7)$$

$$v^+_{uabc} = [v^+_{ua} \quad v^+_{ub} \quad v^+_{uc}]^T = [T_+]v_{uabc} \qquad (8)$$

$$(T_{u+}) = \begin{bmatrix} 1/3 & a^2/3 & a/3 \\ a/3 & 1/3 & a^2/3 \\ a^2/3 & a/3 & 1/3 \end{bmatrix} a = e^{(-j)(\frac{2\pi}{3})} \qquad (9)$$

With the help of transformation given by Clark, the above equations are expressed in terms of αβ and is given by

$$v'_{u\alpha\beta} = \begin{bmatrix} v'_{u\alpha} & v'_{u\beta} \end{bmatrix}^T = [T'_{u\alpha\beta}]v_{uabc} \qquad (10)$$

$$(T_{u\alpha\beta}') = \begin{bmatrix} (1) & (-1/2) & (-1/2) \\ 0 & (\sqrt{3})/2 & -(\sqrt{3})/2 \end{bmatrix} \qquad (11)$$

Finally the instant positive-sequence elements (ISE) of grid voltage with αβ reference frame can be calculated by:

$$v^{+'}_{u\alpha\beta} = [T'_{u\alpha\beta}] * v^+_{uabc} \qquad (12)$$

$$= [T'_{u\alpha\beta}][T_{u+}]\left[T'_{u\alpha\beta}\right]^T v'_{u\alpha\beta} \qquad (13)$$

$$= \left(\tfrac{1}{2}\right)\begin{bmatrix} (1) & -(q) \\ (q) & (1) \end{bmatrix}\begin{bmatrix} v'_{u\alpha} \\ v'_{u\beta} \end{bmatrix} \quad q = e^{(-j)(\frac{\pi}{2})} \qquad (14)$$

Therefore the instant +ve sequence α-β elements of grid voltage are

$$v^{+'}_{u\alpha} = v'_{u\alpha} - qv'_{u\beta} \qquad (15)$$

$$v^{+'}_{u\beta} = v'_{u\beta} + qv'_{u\alpha} \qquad (16)$$

Here q means phase-shift operative element operated in time-domain which achieves the orthogonal phase waveform (lag of 90°) of the fundamental in-phase signal. It is important to have observation is the delay timerepresented by the operator-q is dynamically adjust based on frequency of the in-phase input voltage.

VII. SIMULATION OF MDSOGI

The MDSOGI PLL simulation is carried out using MATLAB Simulink to analysis its results considering different unbalanced conditions, which are affecting synchronization of DGS with its grid.

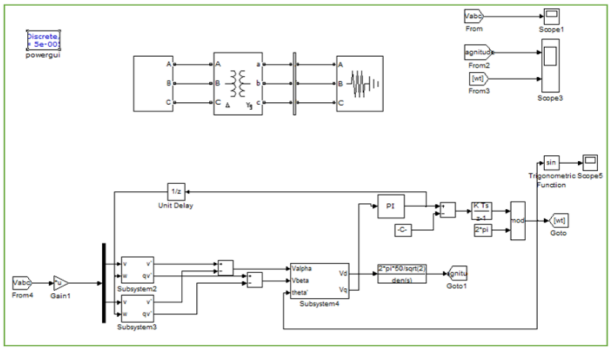


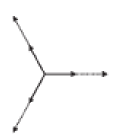
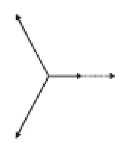
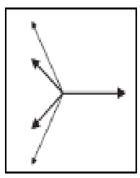
Fig 5: simulation block diagram of MDSOGI-PLL

VIII. RESULTS AND DISCUSSIONS

Input : Before fault: $V^+ = 100\angle 0$ upto 1sec

Frequency of the voltage before fault = 50 Hz [3]

Table 3.1 properties of testing voltage sags [3]

Sag during 3-phase fault	**Sag during single-phase-to ground faults**	**Sag during Phase-to-phase fault**
$V^+ = 40\angle -40$	$V^+ = 73.3\angle -10$	$V^+ = 67.37\angle -5.7$
$V^- = 0\angle 0$	$V^- = 26.6\angle 170$	$V^- = 27.8\angle -2.2$
$V^0 = 0\angle 0$ 	$V^0 = 26.6\angle 170$ 	$V^0 = 0\angle 0$ 

A. SIMULATION RESULTS OF MDDSRF PLL

1. Voltage sag due to 3-phase fault

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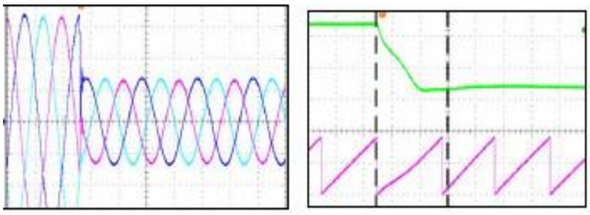
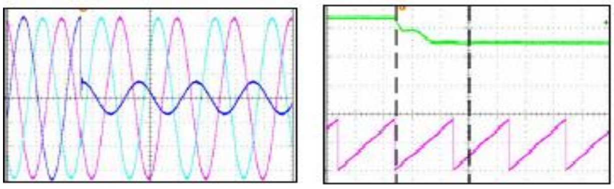


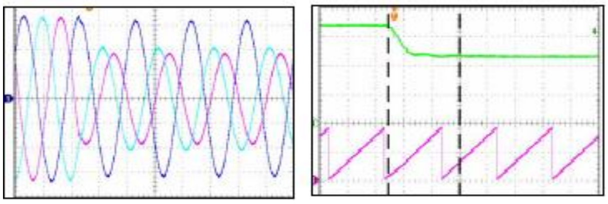
Input Signal & Magnitude and Phase Angle Plot

2. Voltage sag during single phase to ground fault



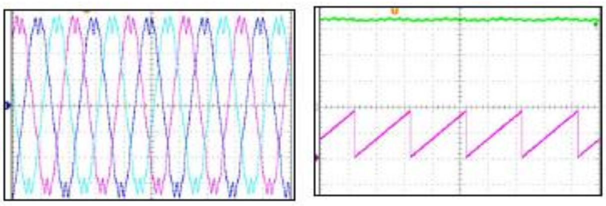
Input Signal & Magnitude and Phase Angle

3. Voltage sag during phase to phase fault



Input Signal & Magnitude and Phase Angle

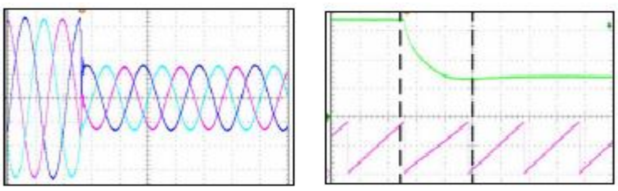
4. Utility voltage with harmonic distortions



Input Signal & Magnitude and Phase Angle

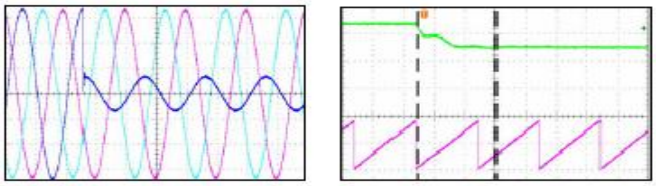
B. SIMULATION RESULTS OF MDDSRF PLL

1. Voltage sag due to 3-phase fault



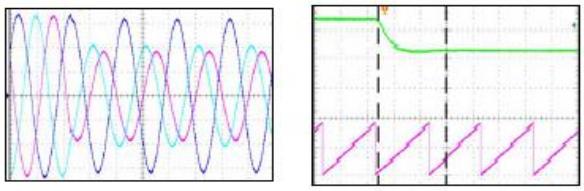
Input Signal & Magnitude and Phase Angle

2. VOLTAGE SAG DURING SINGLE PHASE TO GROUND FAULT



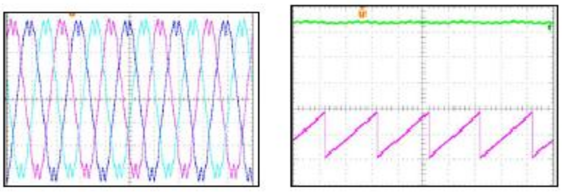
Input Signal & Magnitude and Phase Angle

3. VOLTAGE SAG DURING PHASE TO PHASE FAULT



Input Signal & Magnitude and Phase Angle

4. UTILITY VOLTAGE WITH HARMONIC DISTORTIONS



Input Signal & Magnitude and Phase Angle

IX. COMPARATIVE ANALYSIS OF MDDSRF AND MDSOGI PLL RESULTS:

The main aim of the synchronization techniques discussed in this paper is the determination of +ve sequence d-q axes components of grid voltage during both balanced and unbalanced conditions. The magnitude of grid voltage can be directly observed from +ve sequenced- component and the phase angle plot of grid voltage (positive sequence component) is drawn from utilizing determined +ve sequence q axes-component. But the time required for determination of +ve sequence d-q axes components, quality of the responses, and Mathematical operations carried out in each technique are slightly different. These comparisons of both techniques are tabulated as shown in table 1 & 2.

Table 1 Mathematical operations carried out in MDDSRF PLL and MDSOGI PLL

Technique / Operations	MDDSRF PLL	MDSOGI PLL
Addition	22	38
Multiplication	32	86
Trigonometric	12	4
Division	0	2

Table 2 Simulation result observations of MDDSRF PLL and MDSOGI PLL

Structure	MDDSRF PLL			MDDSRF PLL		
Type of Fault (Grid Unbalances)	Magnitude of grid voltage +ve sequence component (in p.u)	Time taken for finding +ve sequence components	Time Taken for Correction of phase angle	Magnitude of grid voltage +ve sequence component (in p.u)	Time taken for finding +ve sequence components	Time taken for Correction of phase angle
3-Phase Fault	0.4	15.5 ms	25ms	0.4	15.5ms	20ms
Single-phase to ground	0.733	15.2 ms	20ms	0.733	15.3ms	21ms
Phase to phase fault	0.67	15.4 ms	22ms	0.67	15.3ms	22ms

X. CONCLUSION

The presented paper described the response of two advanced grid synchronization PLL based algorithms for DPGS namely MDDSRF PLL and MDSOGI PLL. Here the detailed analysis of these algorithms are discussed with their mathematical analysis and the response of each were carried out using MATLAB Simulink considering different unbalanced sags and distorted utility conditions.

From the output observations of each PLL algorithm it can be conclude that both algorithms are excellently performed in the estimation of positive sequence components of grid reference voltage based on rotating SRF and α-β reference frame. The simplified structure and application of PLL and reference frame techniques provides satisfactory with accurate detection of utility voltage magnitude and its phase-angle within 20-25ms in all conditions.

The rejection capacity of both algorithms against harmonics are tested, the presence of LPF helps in filtering harmonics in MDDSRF PLL and signal generator SOGI itself act as a filter in MDSOGI PLL. Hence both techniques provide good results in elimination process of harmonics.

TheMDDSRF PLL has less execution time and fast closed loop operation as compare to MDSOGI PLL. But the presence of dual SOGI enhance the quality of results with MDSOGI PLL as compares to the results of MDDSRF PLL.

The application of these algorithms may increase the computational cost but provides the better detection of synchronization parameters to DPGS mainly in PV and wind plants.

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