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A Fuzzy-base Hybrid PLL Scheme for Abnormal Grid Conditions

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Abstract— This paper presents a new family of fuzzy phase locked loop (FPLL) -fuzzy double decouple synchronous reference frame phase locked loop (FDDSRF-PLL)- that incorporated DDSRF-PLL into FPLL. FDDSRF-PLL enjoys both advantageous of DDSRF-PLL and fuzzy system to detect the fundamental-frequency positive-sequence component of the utility voltage under unbalanced and distorted conditions as well as fast and smooth tracking of phase jump. Furthermore, to achieve the best possible performance, a fuzzy adaptive particle swarm optimization (FAPSO) algorithm is considered to optimize parameters of the fuzzy system and DDSRF-PLL's filters. The results show that, in comparison with DDSRF-PLL and FPLL, FDDSRF-PLL has better performance in tracking of the positive-sequence voltages of the three-phase system under unbalanced condition, phase and jump simultaneously.

Index Terms— fuzzy double decouple phase locked loop PLL (FDDSRF-PLL), phase jumps, frequency jump, fuzzy adaptive particle swarm optimization (FAPSO), integral of time multiplied squared error (ITAE)

I. INTRODUCTION

In many electronic devices, fast and precise amplitude, phase and frequency estimation of the utility voltage is the foremost aspects in the control of grid connected power converters [1]. Furthermore, fast penetration of renewable energy sources, such as wind power, has introduced stability problems [2]. Hence, the performance of wind turbine generator systems (WTGSs) must be improved to meet grid requirements (GC) [3]. According to grid codes, WTGS must connect to the grid under regular and distorted operating conditions. Under such conditions, the WTGS requires a fast and accurate estimation of the grid voltage amplitude and phase angle to provide the required reactive power at the point of common coupling (PCC).

Different models of PLLs were proposed for grid-connected converters. Among them, synchronous reference frame (SRF) - PLL has attracted more attention than others due to its structure [4]. In spite of its good performance under ideal voltage conditions, the response of the SRF-PLL can deteriorate when utility voltage is unbalanced. The reason for its bad response is that SRF cannot cancel out negative-sequence component during unbalanced conditions. In order to solve this problem, different advanced grid synchronization systems have recently been proposed.

This drawback can be overcome by using a PLL based on the decoupled double synchronous reference frame (DDSRF-PLL) [5], which utilizes two SRFs and a decoupling network to permit a proper isolation of the positive- and negative-sequence components. Another approach with the same idea presented by Xiao *et al.* [6] is a multiple reference frame based PLL (MRF-PLL).

An alternative approach presented by Rodriguez *et al.* [7] is based on a filter concept and is a dual second-order generalized integrator-based PLL (DSOGI-PLL), which works based on the instantaneous symmetrical components (ISC) theory in the stationary $\alpha\beta$ reference frame. This method employs two quadrature signal generators (*QSG*) to separate the negative and positive sequences. In 2013, Beheshtaein presented fuzzy PLL (FPLL) to enhance SRF-PLL performance especially when the grid encounters phase jumps [8].

In power system applications where the power converters need to be synchronized with the grid, phase angle information is of critical significance [9]. Different faulty conditions may induce either abrupt or smooth changes in phase angle; besides adding negative-sequence component and harmonics to positive-sequence component. On the other hand in islanding detection problem, active methods introduce perturbations in the inverter output power [10] such as frequency jump and frequency drift to detect islanding. Moreover, PLL can be used for islanding detection [11].

Observed that PLL have to do with detecting of amplitude and phase of the three-phase voltage, when the system encounters with disturbance, phase jumps and frequency jumps.

In this paper, a new PLL is designed based on DDSRF-PLL, fuzzy PLL, and an evolutionary optimization algorithm. DDSRF-PLL's task is detection of amplitude and phase of the three-phase voltage when the voltage has disturbance; on the other hand, fuzzy-PLL's task is to detect amplitude and phase of the three-phase voltage when the voltage has phase or frequency jumps. Hereupon, a new PLL is being called fuzzy double decouple synchronous reference frame phase locked loop (FDDSRF-PLL).

To increase FDDSRF-PLL performance, the fuzzy adaptive particle swarm optimization (FAPSO) algorithm is used to find appropriate values for parameters of the fuzzy system's and DDSRF-PLL's filters.

II. OVERVIEW OF THE DDSRSRF-PLL AND FUZZY PLL

A. DDSRF-PLL

SRF-PLL is a well-known three-phase PLL also called dqo-PLL. The method used in SRF-PLL includes a rotating reference frame revolving with a phase angle equal to the grid voltage's phase angle. This transformation is done by Park transformation $V_{dqo} = P V_{abc}$ as follows:

$$V_{dqo} = [T_{dq}] V_{abc} \quad (1)$$

where

$$T_{dq} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2}{3} \right) & \cos \left(\theta + \frac{2}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2}{3} \right) & -\sin \left(\theta + \frac{2}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2)$$

The above-stated transformation acts in such a way that keeps the q-component of the grid voltage equal to zero. Then, the q-component of the grid voltage goes through a PI controller to determine the exact grid voltage phase angle.

However, when an unbalanced fault occurs, then the SRF-PLL fails to track accurately the phase angle because V_d does not perfectly match with the positive sequence voltage V^{+1} due to the oscillation which appears as a result of the existence of the negative sequence voltage V^{-1} under unbalanced disturbances.

This drawback can be overcome by using a PLL based on the decoupled double synchronous reference frame (DDSRF-PLL) [12], which utilizes two SRFs and a decoupling network to permit proper isolation of the positive- and negative-sequence components. One SRF rotates with positive synchronous speed, whose angular position is θ and identifies the positive sequence voltage V^{+1} ; and the other one, rotates with negative synchronous speed, whose angular position is $-\theta$ and identifies the negative sequence voltage V^{-1} . The voltage vector V , which consists of V^{+1} and V^{-1} , is established based on dq^{+1} and dq^{-1} reference frames as follows:

$$V_{dq^{+1}} = [T_{dq^{+1}}] V_{\alpha\beta} = V^{+1} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + V^{-1} \begin{bmatrix} -\cos 2\omega t \\ -\sin 2\omega t \end{bmatrix} \quad (3)$$

$$V_{dq^{-1}} = [T_{dq^{-1}}] V_{\alpha\beta} = V^{-1} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + V^{+1} \begin{bmatrix} +\cos 2\omega t \\ +\sin 2\omega t \end{bmatrix} \quad (4)$$

where

$$[T_{dq^{+1}}] = [T_{dq^{-1}}]^T = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \quad (5)$$

The results of the decoupling cells are the V_{dq}^{+1*} and V_{dq}^{-1*} , which are almost DC terms and through a low pass filter (LPF) could be used for monitoring the grid voltage. V_q^{+1} is approached to zero to let V_d^{+1*} follow the real amplitude of the three-phase voltage. The DDSRF-PLL scheme is shown in Fig. 1.

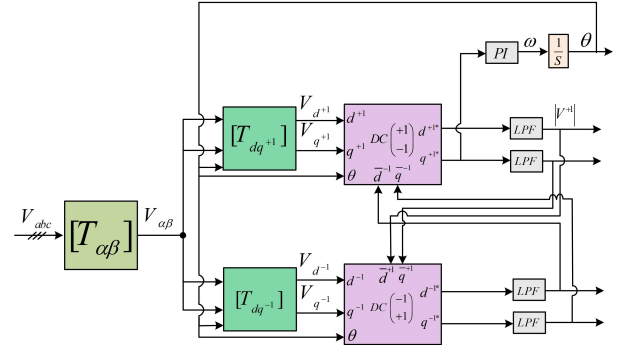


Fig. 1. Block diagram of the DDSRF PLL.

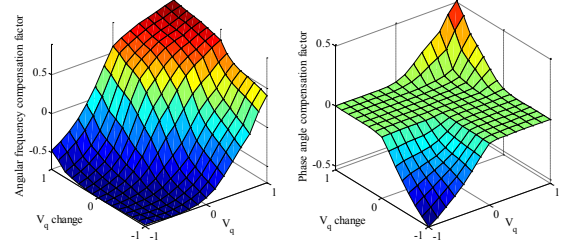


Fig. 2. Angular frequency change and phase angle change behaviors during the different conditions.

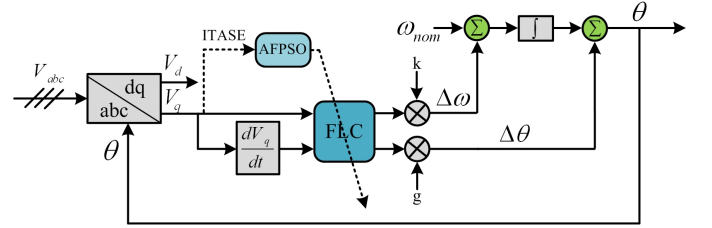


Fig. 3. Block diagram of the FPLL.

B. Fuzzy PLL

Fuzzy PLL was designed based on substitution of PI controller with fuzzy logic controller (FLC) in SRF-PLL. The reasoning behind designing a fuzzy phase locked loop is that every phase angle jump can be followed by changing angular frequency ($\Delta\omega$) and phase angle ($\Delta\theta$). Angular frequency change and phase angle change is applied for subtle and abrupt changes, respectively. Therefore, the fuzzy rule base for angular frequency change and phase angle change is determined based on the following expressions.

- 1) When a very large positive (or negative) change in phase angle is sensed, angular frequency change and phase angle change will be assigned large positive (or negative) values.
- 2) When a large negative (or negative) change in phase angle is sensed, angular frequency change and phase angle change will be assigned large positive (or negative) and small positive (or negative) values, respectively.
- 3) When a very large positive (or negative) change in phase angle is sensed, angular frequency change and

phase angle change will be assigned large positive (or negative) values.

- 4) When a large negative (or negative) change in phase angle is sensed, angular frequency change and phase angle change will be assigned large positive (or negative) and small positive (or negative) values, respectively.

In other words, angular frequency and phase angle compensation factors must indicate gradual and sudden manners, respectively, as depicted in Fig. 2.

The q-axis component of grid voltage and a derivative of the q-axis component of grid voltage are considered to feed FLC. Moreover, the FLC confines output between zero and one. To have variables with different ranges, two variables are multiplied by FLC's outputs. These parameters are shown in Fig. 3 with k and g. A comprehensive model of a fuzzy PLL is depicted in Fig. 3.

III. PROPOSED METHOD

A. DDSRF-PLL and FPLL performance

The main drawback of the DDSRF-PLL is the high overshoot in the phase angle and frequency estimation, which appears at the instant the grid fault, occurs. Besides, high settling time in response to the phase and frequency changes. The DDSRF-PLL's performance under a grid fault condition and 40 degree phase jump is illustrated in Fig. 4.

On the other side, during the unbalanced conditions, Fuzzy PLL is not able to detect amplitude and phase of the positive sequence component of the three-phase voltage. The Fuzzy PLL's performance under the unbalanced voltage and 40 degree phase jump is illustrated in Fig. 5.

B. FDDSRF-PLL

According to mentioned advantages and disadvantages of DDSRF-PLL and Fuzzy PLL, these two PLLs are complementary to each other; in other words, a new hybrid PLL can be created based on DDSRF-PLL and Fuzzy PLL to have better performance under the unbalanced condition besides phase and frequency jumps. This hybrid PLL is also called FDDSRF-PLL.

FDDSRF-PLL assigns the task of detecting the amplitude and phase of the positive sequence component of the three-phase voltage in unbalanced conditions to DDSRF-PLL and in the phase or frequency jumps to Fuzzy PLL.

In DDSRF-PLL part, decoupling cells takeover the job of canceling out the effect of negative-sequence component to positive sequence, which result in no oscillation in positive-sequence component of voltage and perfect detection of amplitude and phase of the three-phase voltage.

In Fuzzy PLL part, position of counterclockwise rotating reference frame (dq^{+1}) is adjusted by FLC in such a way to keep q-axis component of voltage equal to zero. This result in quick following of positive component of three-phase voltage

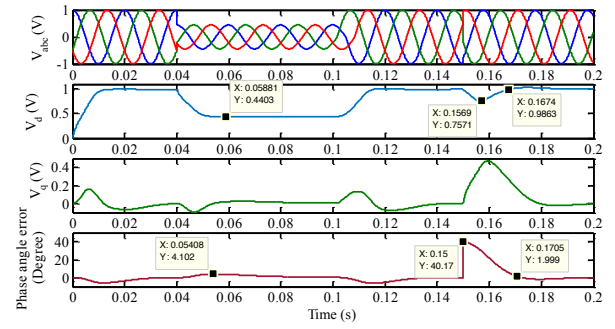


Fig. 4. DDSRF-PLL's performance under the grid fault and 40-degree phase jump.

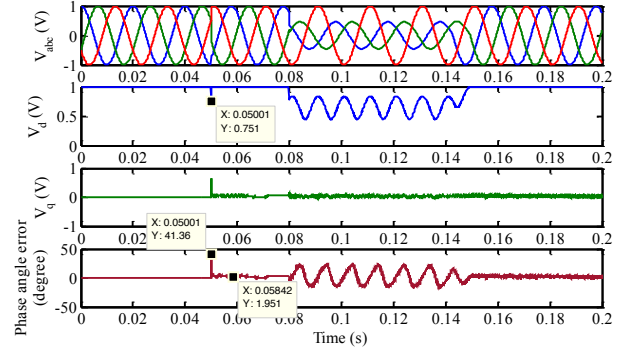


Fig. 5. FPLL's performance under the grid fault and 40-degree phase jump

even in the sudden phase and frequency jumps. The overall scheme of FDDSRF-PLL is illustrated in Fig. 6.

C. Optimized FDDSRF-PLL

The proposed structure is in its maximum performance when FLC's membership functions parameters and filters' parameters of DDSRF-PLL are at their optimum values. In this paper the integral of time multiplied absolute error (ITAE) is considered the cost function to evaluate the system's performance during all conditions including unbalanced condition, phase and frequency jumps. ITAE can be evaluated as

$$ITAE = \sum_{t=1}^n \Delta T_s |V_q^{+1}|_{t=i} - |V_q^{+1}|_{t=i-1}| \quad (6)$$

In this paper, minimum value of (6) is attained by FAPSO algorithm. The optimization block and its objective function are shown in Fig. 6.

In this regard, FAPSO is proposed to accelerate determination of a global minimum. Particle swarm optimization (PSO) is based on simulation of a flock of birds searching for food. In this simulation, each bird has its own velocity; however the movement of others can affect an individual bird's velocity and direction. This is usually dependent on one or another of the following behavioral stimulants: inertia, cognitive stimulant, and social stimulant. Inertia is the tendency to continue in a previously set direction. The cognitive stimulant models a bird's memory of a previous best position. The social stimulant models a bird's memory of the best position among birds.

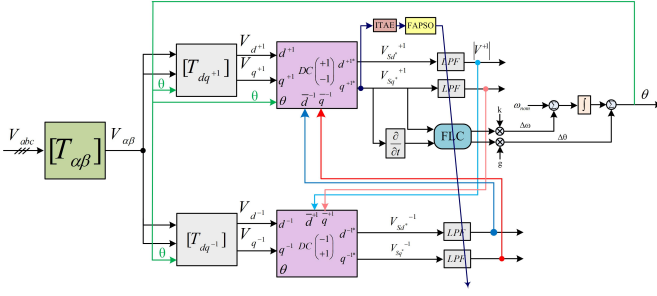


Fig. 6. Block diagram of FDDSRF-PLL.

According to the discussion above, the mathematical model for PSO is as follows:

$$\begin{aligned}
 V_i^{t+1} &= \omega \times V_i^t + C_1 \times rand_1(.) \times (Pbest_i - X_i^t) + \dots \\
 &C_2 \times rand_2(.) \times (Gbest_i - X_i^t) \\
 X_i^{t+1} &= X_i^t + V_i^{t+1} \\
 i &= 1, 2, 3, \dots, N_{swarm}
 \end{aligned} \quad (4)$$

where C_1, C_2 are called learning factors and ω is inertia weight. In an original PSO algorithm, the above parameters hold constant. Inertia weight controls the next iteration speed. C_1 is considered a cognitive parameter due to its ability to follow its own best value; however, C_2 is for tracking Gbest. By utilizing the fuzzy system the learning factors and inertia weight can be properly determined based on the number of best fitness (BF) and the number of unchanged fitness (NU).

The BF value determines performance to identify the best candidate to represent a solution found so far. In order to apply BF to a fuzzy system, this parameter should be normalized using the following formula:

$$NBF = \frac{BF - BF_{\min}}{BF_{\max} - BF_{\min}} \quad (5)$$

where BF_{\max} and BF_{\min} are maximum and minimum values of best fitness value. NU value is also normalized in a similar way.

The output of the fuzzy system is C_1, C_2 and ω . These parameters are confined in the range as follows: $0.2 \leq \omega \leq 1.2$ and $0.2 \leq C_1, C_2 \leq 1.2$.

Fuzzification of the fuzzy system is done by the triangular and trapezoidal membership functions shown in Fig. 7.

In the inference engine, fuzzy rules can be determined according to the following expressions [12]:

- I. When best fitness (BF) is found at the end of the run, higher learning factors and a lower inertia weight is desired.
- II. When the best fitness does not change during a run, the learning factors should be increased and the inertia weight should be decreased.

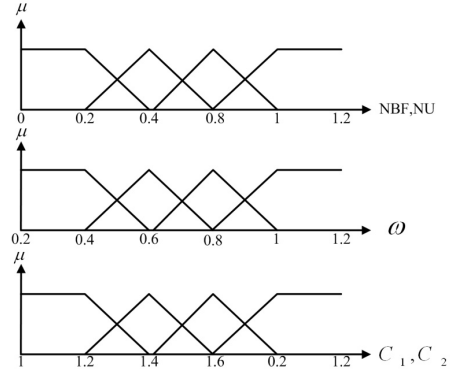


Fig. 7. Membership functions of inputs and outputs: (a) NBF or NU, (b) ω , and (c), C_1, C_2 .

TABLE I. Fuzzy rule for learning factor C_1 .

C_1		NU			
		PS	PM	PB	PR
NBF	PS	PR	PB	PB	PB
	PM	PB	PM	PM	PS
	PB	PB	PM	PS	PS
	PR	PM	PM	PS	PS

TABLE II. Fuzzy rule for learning factor C_2 .

C_2		NU			
		PS	PM	PB	PR
NBF	PS	PR	PB	PM	PM
	PM	PB	PM	PS	PS
	PB	PM	PM	PS	PS
	PR	PM	PS	PS	PS

TABLE III. Fuzzy rule for learning factor ω .

ω		NU			
		PS	PM	PB	PR
NBF	PS	PR	PB	PM	PM
	PM	PB	PM	PS	PS
	PB	PM	PM	PS	PS
	PR	PM	PS	PS	PS

Accordingly, rules for the adaptation process are demonstrated in Tables I, II, and III. Centroid (center of sum) is also taken into account for defuzzification.

IV. SIMULATION AND RESULTS

The input signal is initially made balanced and sinusoidal with unity magnitude and 50-HZ frequency. Then a three-phase fault and a 40-degree phase jump are sequentially applied. The fuzzy PLL is simulated using MATLAB.

A. Designing fuzzy PLL based on a three-phase fault and a 40-degree phase jump

In the first step, the FDDSRF-PLL is built based on Fig. 6. Although this paper considers FAPSO to optimize FLC, any other evolutionary algorithms can be utilized. Generally, optimization processes of the FDDSRF-PLL for the grid fault between 0.04 to 0.1 and a 40-degree phase jump at $t=0.15$ s can be summarized as follows.

Step 1: The initial population and initial velocity for each particle should be generated randomly.
Step 2: The objective function (ITAE) is to be evaluated for each individual.
Step 3: The individual that has the minimum ITAE should be selected as the global position.
Step 4: The i^{th} individual is selected.
Step 5: The best local position (Pbest) is selected for the i^{th} individual.
Step 6: FAPSO parameters are updated.
Step 7: The next position for each individual is calculated based on FAPSO parameters and (4) and then checked with its limit.
Step 8: If all individuals are selected, go to the next step; otherwise $i = i + 1$ and go to step 4.
Step 9: If the current iteration number reaches the predetermined maximum iteration number (this paper considers 100 for maximum iteration), the search procedure is stopped; otherwise go to step 2.

The last Gbest is the solution of the problem. The FAPSO algorithm tries to approach optimum solution iteration by iteration. Fig. 8 shows convergence of solution to optimum solution is attained at 40th iterations.

Although the FAPSO algorithm attempts to minimize the ITAE of the q-axis component of the grid voltage, the main result after the optimization process would be fast tracking of phase angle after applying a 40-degree phase angle jump. Fig. 9 illustrates deviation in d- and q- axis components of the grid voltage. The fast and precise response of the FDDSRF-PLL results from its structure. Once the FDDSRF-PLL senses abrupt change in the q-axis component of the grid voltage and corresponding phase angle, it exerts two components simultaneously to eliminate phase angle error. These components include angular frequency and phase angle compensation factors, with the roles of slow and smooth compensation for the first factor as well as fast compensation for the second one. In other words, angular frequency and phase angle compensation factors must indicate gradual and sudden manners, respectively, as depicted in Fig. 2. On the other hand, decoupling cells of DDSRF-PLL cancel out the effect of the negative sequence component on the positive sequence component.

A comparison of performance of DDSRF-PLL (see Fig. 4), FPLL (see Fig.5), and FDDSRF-PLL (see Fig. 9) is shown in Table IV. It is obvious from Table IV that the FDDSRF-PLL has a very efficient capability of tracking phase angle in 6.8 ms, although it causes an 1.23 degree overshoot at $t=0.15$ second. FDDSRF-PLL solves the problem of voltage oscillation in the FPLL during the grid fault; moreover, the settling time of positive-sequence component for the grid fault is lower than the two other PLLs.

One of the advantages of the FDDSRF-PLL is robustness of the voltage amplitude against any phase jumps. Hence, this PLL can be used specially when control system operates based on only voltage's amplitude.

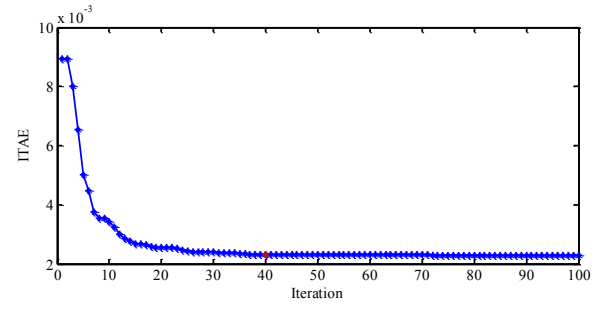


Fig. 8. Convergence characteristics of the FAPSO algorithm for optimizing FDDSRF-PLL.

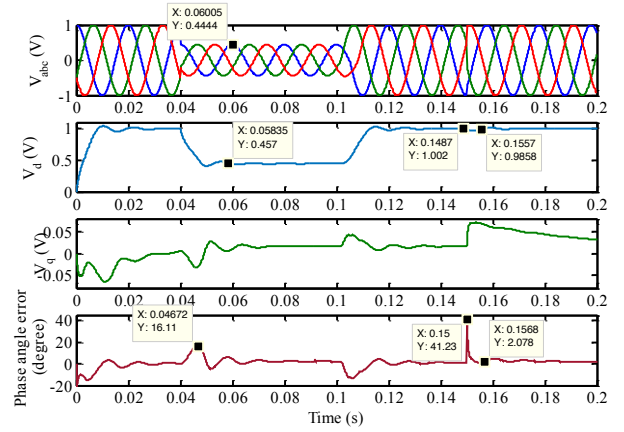


Fig. 9. Performance of the FDDSRF-PLL under the three-phase fault at 0.04 s, and a phase jump equal to 40-degree at $t=0.15$ s.

TABLE IV. Summary of the different PLLs' performance against a the grid fault and 40 degree phase jump.

	DDSRF-PLL	FPLL	FDDSRFR-PLL
40 ° Jump			
Settling time	20 ms	8.4 ms	6.8 ms
Angle's overshoot	0.17°	1.36°	1.23°
Amplitude's undershoot	0.233 p.u.	0.23 p.u.	0.014 p.u.
Three-phase fault			
Settling time	8.8 ms	---	8.3 ms
Phase jump	4.102°	22.07°	16.1°

B. Testing tuned the FDDSRF-PLL for other phase jumps

To verify the FDDSRF-PLL performance, other kinds of phase jumps are taken into account. The phase jumps are divided into two categories. The first category is positive phase jump. Here, a 20-degree phase jump is selected to verify that the FDDSRF-PLL has the same performance as it had against the 40-degree phase jump. The second category is negative phase jumps, including a -30-degree phase jump. Negative phase jumps are essential for testing fuzzy PLL performance, because the system was designed based on a 40-degrees phase jump, thus logically the phase angle compensation factor must be positive. Nevertheless, the only remaining question is: does FDDSRF-PLL have the same speed in tracking phase angle after facing negative phase jumps or 40-degree phase jumps?

In this regard, 20-degree and -30-degree phase jumps are set at $t=0.15$ to assess the FDDSRF-PLL performance. Fig. 10 shows that the FDDSRF-PLL has only a 1.23-degree overshoot and reaches the accurate phase angle after 4.1 ms

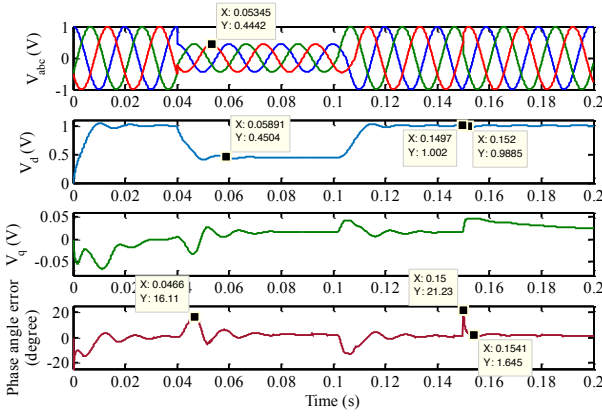


Fig. 10. Performance of the FDDSRF-PLL under the three-phase fault at 0.04 s, and a phase jump equal to 20-degree at t=0.15 s.

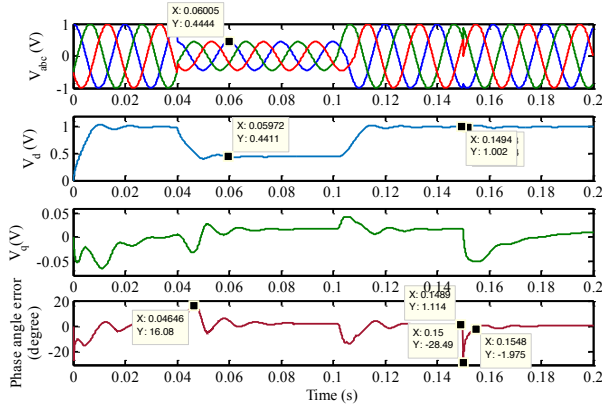


Fig. 11. Performance of the FDDSRF-PLL under the three-phase fault at 0.04 s, and a phase jump equal to -30-degree at t=0.15 s.

This indicates that both settling time becomes low. Moreover in -30-degree phase jumps, settling time and overshoot are equal to 4.8 ms and -0.39 degrees, respectively. It must be noted that as phase angle error before phase jump is 1.114, then overshoot is -0.39° (See Fig. 11).

These results indicate that even though negative phase jump misleads the estimation of phase angle by applying a positive phase angle change in the first instant of disturbance, (This parameter is determined based on a 40-degree phase jump.), tracking of phase angle is performed with approximately the same settling time as other positive phase jumps. In other words, the FDDSRF-PLL has a very efficient fuzzy rule base that can reject any positive and negative phase jumps at less than 6.8 ms.

V. CONCLUSION

This paper has introduced and discussed a FDDSRF-PLL structure based on the concept of a fuzzy logic controller, the double decoupling blocks in DDSRF-PLL, and FAPSO algorithm. According to FDDSRF-PLL, angular frequency and phase angle compensation factors were designed to compensate for the required phase angle and to track phase angle rapidly. Angular frequency and phase angle compensation factors track

delicate and abrupt variations of phase angle, respectively. Furthermore, the decoupling blocks eliminate the effect of negative-sequence component to positive sequence the voltage. Hence the FDDSRF-PLL takes advantage of fast phase jump tracking and accurate detection of the grid voltage amplitude during the grid fault from the FPLL and DDSRF-PLL, respectively. Finally, the FDDSRF-PLL had been optimized based on FAPSO algorithm.

The results show that the FDDSRF-PLL has the capability of tracking phase angle and voltage amplitude after encountering various phase jumps and the grid fault. Regardless of sign or magnitude of phase jumps, fuzzy PLL track the grid voltage phase angle in less than 6.8 ms. Furthermore, voltage amplitude do not experience any oscillations and it is robust against any phase jumps. As a result, this method is a great candidate to control power electronic devices.

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