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A New Three-Phase Looked Loop Based on Double Synchronous Coordinate Transform and Cross Decoupling

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Abstract. In order to accurately detect the load harmonic current, a new three-phase looked loop based on double synchronous coordinate transform and cross decoupling is proposed in this paper. It improves the phase lock precision, and increases the effectiveness of ripple elimination. Compared with harmonic detection simulation result of traditional phase locked loop (SRF-PLL) used in i_p-i_q method, it shows that the fundamental current distortion can be extracted more by the new phase lock loop (IDDSRF-PLL) has reduced by 1.18% and 1.42% under grid voltage unbalanced and distortion circumstances, so the loop has better harmonic detection performance.

Keywords: Harmonic detection, Double synchronous rotating coordinate, Active power filter, Three-phase unbalance

1. Introduction

In recent years, with a large number of nonlinear loads widely used in the industrial and civil field, power grid current wave is more and more seriously distorted, and the harm of harmonic to power grid is becoming more and more obvious. Passive filter (PF), as the traditional management device, is widely used for it has characteristics of simple structure, low cost, high operation reliability. compared with PF, APF has several advantages [1] : 1) APF are not affected by system impedance; 2) APF won't cause other equipments damaged because of overload; 3) compensation effect is not affected by the change of load; 4) when APF dispose of harmonic , it can compensate reactive power, adjust the load balance, and reduce voltage flicker at the same time.

As the important link of APF, harmonic detection can directly affect the performance of the APF. At present, the instantaneous reactive power theory detection method is widely applied because it can rapidly and accurately detect the harmonic current. However, traditional methods can't carry accurate detection under power grid imbalance, distortion and serious interference, so a variety of improved detection methods are proposed [2]. According to the disadvantages of this method, researchers do a lot work on the improvement of the phase lock link. In paper [3, 4], traditional phase lock loop SRF-PLL is proposed based on synchronous coordinate transformation. This phase lock loop can accurately locks phase, but a large number of ripples will be produced in early detection when voltage imbalance happens. According to the defects of traditional phase lock loop, this paper puts forward an adaptive phase lock loop SRF-PLL [5], it can avoid frequency fluctuation as phase jumps in the soft start stage, but it can also increase of the complexity of the algorithm. In [6, 7], specific "filter" technology is proposed, the technology improves the performance of SRF-PLL through extracting fundamental positive sequence component, but the double frequency component caused by fundamental frequency of the negative sequence component can bring error in the detection link. [8-10] proposes decoupling phase locked loop based on double synchronous coordinate system, the biggest advantage of decoupling phase locked loop is that it can eliminate the double frequency

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[+] Corresponding author. *E-mail address*: zhangwenlong2010@yahoo.cn component, realize accurate tracking of phase and frequency. Work [11] studies on how to inhibit ripple, it puts forward an integral circuit, and its simulation results prove that it can achieve expected effect.

Based on the literature [8-11], IDDSRF-PLL phase lock loop is proposed in this paper. The new phase lock loop not only can better detect phase and frequency in power grid imbalance and distortion conditions, but also can better inhibit ripple, improve the precision of the harmonic detection.

2. Decoupling and phase lock principle of double synchronous coordinate system

The theory is proposed based on the influence that power grid voltage negative sequence component brings to the traditional phase lock loop [8,]. The following is an example of unbalance voltage under double synchronous coordinate system.

Three-phase asymmetrical voltage can be expressed as:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = U^{+1} \begin{bmatrix} \cos(wt+\varphi_{+1}) \\ \cos(wt-\frac{2\pi}{3}+\varphi_{+1}) \\ \cos(wt+\frac{2\pi}{3}+\varphi_{+1}) \end{bmatrix} + U^{-1} \begin{bmatrix} \cos(wt+\varphi_{-1}) \\ \cos(wt-\frac{2\pi}{3}+\varphi_{-1}) \\ \cos(wt+\frac{2\pi}{3}+\varphi_{-1}) \end{bmatrix} + U^{0} \begin{bmatrix} \cos(wt+\varphi_{0}) \\ \cos(wt+\varphi_{0}) \\ \cos(wt+\varphi_{0}) \end{bmatrix} \tag{1}$$

Here, U^{+1}, U^{-1}, U^{0}, φ_{+1}, φ_{-1}, φ_{0} are amplitude and initial phase of the positive sequence, negative sequence, and zero sequence component of three-phase voltage, respectively. In order to eliminate the influence of the zero sequence components, three-phase voltage can be transformed to the αβ coordinate system (for convenient calculation, setφ +1= 0).

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = U^{+1} \begin{bmatrix} \cos wt \\ \sin wt \end{bmatrix} + U^{-1} \begin{bmatrix} \cos(-wt+\varphi_{-1}) \\ \sin(-wt+\varphi_{-1}) \end{bmatrix} \tag{2}$$

The following equations can be obtained after transforming equation (2) to double synchronous coordinate system:

$$U_{dq^{+1}} = \begin{bmatrix} U_{d^{+1}} \\ U_{q^{+1}} \end{bmatrix} = \begin{bmatrix} T_{dq^{+1}} \end{bmatrix} U_{\alpha\beta} = U^{+1} \begin{bmatrix} \cos(wt-\theta^{'}) \\ \sin(wt-\theta^{'}) \end{bmatrix} + U^{-1} \begin{bmatrix} \cos(-wt+\varphi_{-1}-\theta^{'}) \\ \sin(-wt+\varphi_{-1}-\theta^{'}) \end{bmatrix} \tag{3}$$

$$U_{dq^{-1}} = \begin{bmatrix} U_{d^{-1}} \\ U_{q^{-1}} \end{bmatrix} = \begin{bmatrix} T_{dq^{-1}} \end{bmatrix} U_{\alpha\beta} = U^{-1} \begin{bmatrix} \cos(wt+\theta^{'}) \\ \sin(wt+\theta^{'}) \end{bmatrix} + U^{-1} \begin{bmatrix} \cos(-wt+\varphi_{-1}+\theta^{'}) \\ \sin(-wt+\varphi_{-1}+\theta^{'}) \end{bmatrix} \tag{4}$$

here， $\begin{bmatrix} T_{dq^{+1}} \end{bmatrix} = \begin{bmatrix} T_{dq^{-1}} \end{bmatrix}^T = \begin{bmatrix} \cos\theta^{'} & \sin\theta^{'} \\ -\sin\theta^{'} & \cos\theta^{'} \end{bmatrix}$

Double synchronous coordinate system includes two rotating coordinate system. Positive synchronous rotating coordinate system dq^{+1} rotates anti-clockwise at $w^{'}$ angular velocity, rotation angle is $\theta^{'}$, and negative synchronous rotates clockwise at $-w^{'}$ angular velocity, rotation angle is $-\theta^{'}$. Voltage vector diagram is as shown in figure 1.

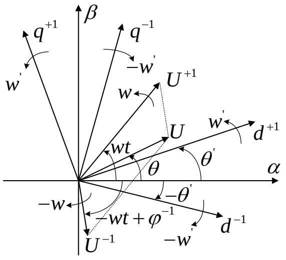

Fig.1 Voltage vectors and axes of the DSRF

If phase is locked, then $\theta' \approx wt$, $\sin(wt-\theta') \approx wt-\theta'$, $\cos(wt-\theta') \approx 1-((wt-\theta')^2/2)$, substitute them into (3) ~ (4), and obtain:

$$\begin{bmatrix} U_{d^{+1}} \\ U_{q^{+1}} \end{bmatrix} \approx U^{+1} \begin{bmatrix} 1-((wt-\theta')^2/2) \\ wt-\theta' \end{bmatrix} + U^{-1} \begin{bmatrix} \cos(-2wt+\varphi_{-1}) \\ \sin(-2wt+\varphi_{-1}) \end{bmatrix} \quad (5) \qquad \begin{bmatrix} U_{d^{-1}} \\ U_{q^{-1}} \end{bmatrix} \approx U^{+1} \begin{bmatrix} \cos(2wt) \\ \sin(2wt) \end{bmatrix} + U^{-1} \begin{bmatrix} \cos(\varphi_{-1}) \\ \sin(\varphi_{-1}) \end{bmatrix} \quad (6)$$

From (5) ~ (6), it can be known that there is double frequency component in unbalance voltage after transformation and double synchronous transform. In order to get dc component of positive sequence component in each phase, cross decoupling algorithm was applied to eliminate the double frequency component in this paper.

The transform formula is simplified to:

$$\begin{bmatrix} \mathrm{U}^*_{d^{+1}} \\ \mathrm{U}^*_{q^{+1}} \end{bmatrix} = \begin{bmatrix} U_{d^{+1}} \\ U_{q^{+1}} \end{bmatrix} - \overline{U}_{d^{-1}} \begin{bmatrix} \cos(2wt) \\ -\sin(2wt) \end{bmatrix} - \overline{U}_{q^{-1}} \begin{bmatrix} \sin(2wt) \\ \cos(2wt) \end{bmatrix} \quad (7) \qquad \begin{bmatrix} \mathrm{U}^*_{d^{-1}} \\ \mathrm{U}^*_{q^{-1}} \end{bmatrix} = \begin{bmatrix} U_{d^{-1}} \\ U_{q^{-1}} \end{bmatrix} - \overline{U}_{d^{+1}} \begin{bmatrix} \cos(2wt) \\ \sin(2wt) \end{bmatrix} \quad (8)$$

Low-pass filtering link is applied in this paper to reduce the influence system harmonic brings to synchronous phase lock loop. Through extracting positive sequence component, $U^*_{q^{+1}} = 0$, so the amplitude, phase and frequency of positive sequence, negative sequence component can be accurately output by the phase lock loop.

Though it is proposed above that there is double frequency component in unbalance voltage after transformation and double synchronous transform and can be eliminated by cross decoupling algorithm, the effect is not ideal. So, this paper puts forward a new method [11].

According to (7), $\mathrm{U}^*_{d^{+1}}$ 、 $\mathrm{U}^*_{q^{+1}}$ can be simplified as:

$$\begin{cases} \mathrm{U}^*_{d^{+1}} = K\cos(2wt+\varphi_{+1}) \\ \mathrm{U}^*_{q^{+1}} = C - K\sin(2wt+\varphi_{+1}) \end{cases} \quad (9)$$

Here C is constant, K is a coefficient.

In equation (9), take the derivative of $\mathrm{U}^*_{q^{+1}}$:

$$\frac{d\mathrm{U}^*_{q^{+1}}}{dt} = -K2w\cos(2wt+\varphi_{+1}) \quad (10)$$

Combine (9) with (10), the ripple of $\mathrm{U}^*_{d^{+1}}$ can be eliminated by following computation.

$$\mathrm{U}^*_{dif} = \mathrm{U}^*_{d^{+1}} + \frac{1}{2w}\frac{d\mathrm{U}^*_{q^{+1}}}{dt} = 0 \quad (11)$$

It can be seen from (11) that error signal does not contain ripple.

In conclusion, the algorithm process of improving double synchronous coordinate system decoupling phase lock loop is as follows:

1) Through abc-$\alpha\beta$ transformation, transform unbalanced three-phase voltage U_{abc} to U_α and U_β form.

2) Through $\alpha\beta$-dq^{+1} and $\alpha\beta$-dq^{-1} transformation, transform U_α and U_β to $U_{dq^{+1}}$ and $U_{dq^{-1}}$ respectively.

3) Through cross decoupling algorithm, transform $U_{dq^{+1}}$ and $U_{dq^{-1}}$, get $\mathrm{U}^*_{d^{+1}}$, $\mathrm{U}^*_{q^{+1}}$, $\mathrm{U}^*_{d^{-1}}$ and $\mathrm{U}^*_{q^{-1}}$.

4) Take the derivative of $\mathrm{U}^*_{q^{+1}}$ and add it to $\mathrm{U}^*_{d^{+1}}$, get:

$$\mathrm{U}^*_{dif} = \frac{1}{2w}\frac{d\mathrm{U}^*_{q^{+1}}}{dt} + \mathrm{U}^*_{d^{+1}} \quad (12)$$

5) U^*_{dif} minus U^*_{d0}, get error signal U^*_{derr}. Set the error signal as PI regulator's input when computing the angular frequency change, and obtain:

$$\Delta w = K_p\mathrm{U}^*_{derr} + K_iT_s\mathrm{U}^*_{derr} \quad (13)$$

6) Add Δw to reference angular frequency w_0, get angular frequency.

$$w = \Delta w + w_0 \quad (14)$$

7) The expected phase angle θ' is get by the use of integral circuit,

$$\theta'_k = \theta'_{(k-1)} + T_s w_{(k-1)} \qquad (15)$$

According to the above algorithm, the principle diagram of improved double synchronous coordinate system decoupling phase lock loop can be obtained as shown in figure 2.

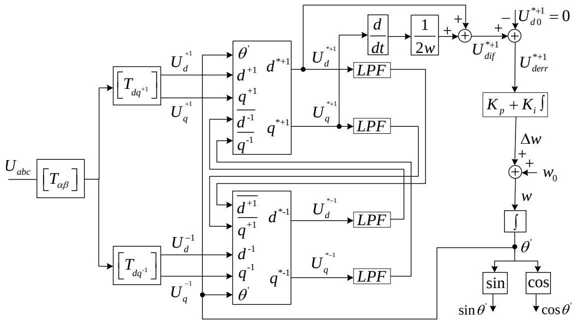

Fig.2 Principle diagram of a IDDSRF-PLL

3. The simulation research

In order to validate harmonic detection performance of the improved phase lock loop based on instantaneous reactive power theory, this paper use Matlab2011b simulate the harmonic detection process of the traditional instantaneous reactive power detection method (i_p-i_q), instantaneous reactive power detection based on the SRF-PLL (SRF-PLL_ i_p-i_q), and instantaneous reactive power method based on the IDDSRF-PLL (IDDSRF-PLL_ i_p-i_q) in three different power grid voltage levels.

Specific parameters are as follows: positive sequence fundamental wave phase voltage of grid is 120v (50Hz); grid resistance and inductance are R_s=0.03Ω, L_s=1.0mH respectively; Harmonic source is a three-phase rectifier bridge with resistive load, which forward voltage is 5v, here, the resistance is R=15Ω and inductance is L=10mH.

Single-phase grounding fault detection

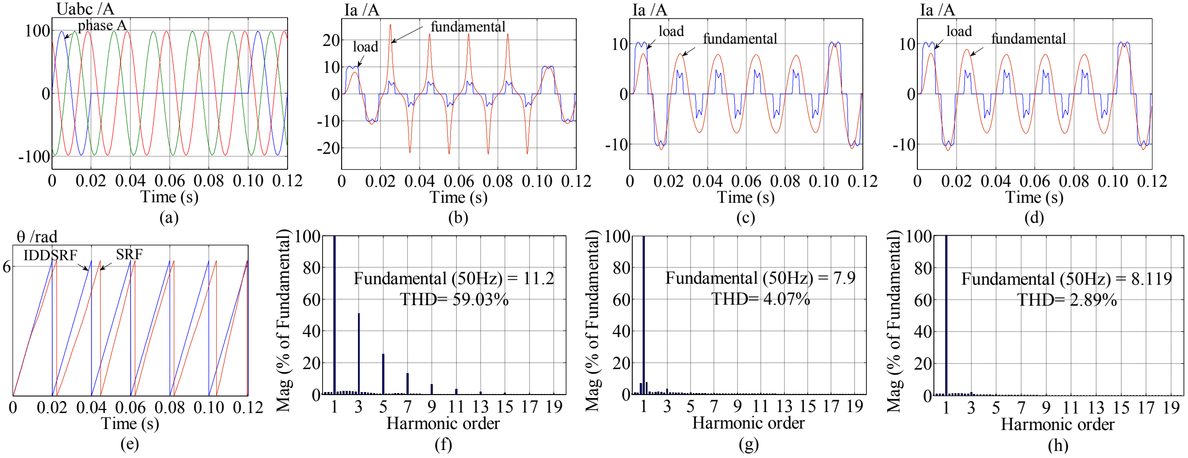

Fig.3 Single phase to ground fault. (a) three-phase voltage; (b) fundamental current extracted by traditional i_p-i_q method; (c) fundamental current extracted by SRF-PLL_ i_p-i_q method; (d) fundamental current extracted by IDDSRF-PLL_ i_p-i_q method; (e) output phase angular of locked loop; (f) frequency spectrum of fundamental current extracted by traditional i_p-i_q method; (g) frequency spectrum of fundamental current extracted by SRF-PLL_ i_p-i_q method; (h) frequency spectrum of fundamental current extracted by IDDSRF-PLL_ i_p-i_q.

As single-phase ground fault of power grid, figure 4 (a) shows a ground fault happens in phase A at 0.02s to 0.10s, then at 0.10s fault disappears. From figure 3(f)-(h) it can be known that, in case of single-phase ground fault, the fundamental current distortion can be extracted 59.03% using traditional algorithm, so it can't accurately detect the harmonic current. However, the fundamental current distortion can be extract

4.07% and 2.89% respectively by SRF-PLL_i_p-i_q and IDDSRF-PLL_ i_p-i_q; this indicates that SRF-PLL_ i_p-i_q method and IDDSRF-PLL_ i_p-i_q method can accurately detect the harmonic current in power grid single-phase ground fault. What's more, by comparing the output Angle of phase lock loop, it can be drawn that IDDSRF-PLL_ i_p-i_q method is superior to the SRF-PLL_ i_p-i_q method.

Detection of power grid voltage including harmonic negative sequence component

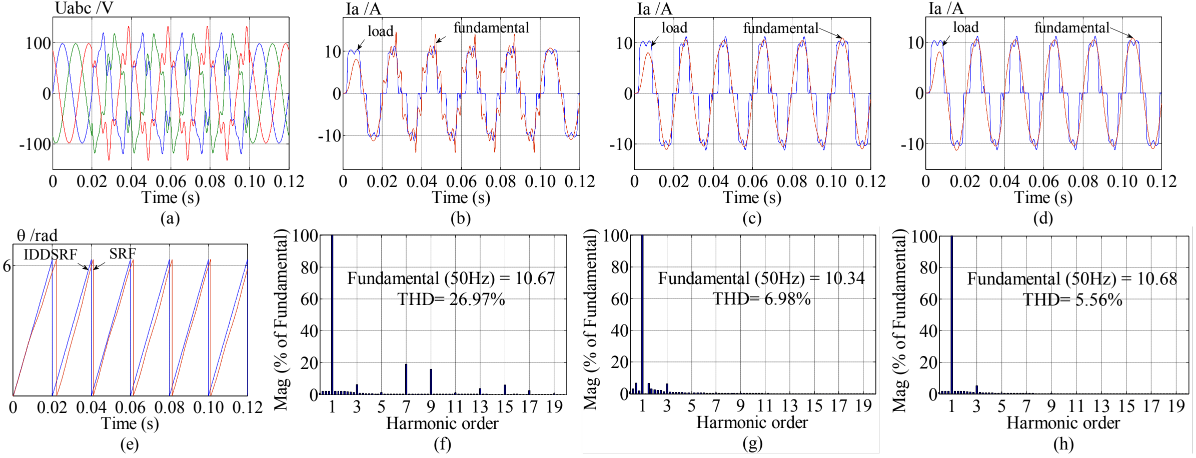

Fig.4 Grid voltage with harmonic, negative component. (a) three-phase voltage; (b) fundamental current extracted by traditional i_p-i_q method; (c) fundamental current extracted by SRF-PLL_ i_p-i_q method; (d) fundamental current extracted by IDDSRF-PLL_ i_p-i_q method; (e) output phase angular of locked loop; (f) frequency spectrum of fundamental current extracted by traditional i_p-i_q method; (g) frequency spectrum of fundamental current extracted by SRF-PLL_ i_p-i_q method; (h) frequency spectrum of fundamental current extracted by IDDSRF-PLL_ i_p-i_q.

For power grid voltage including harmonic negative sequence components, figure 4(a) shows that, 5th and 7th negative sequence harmonic are insert into three-phase voltage at 0.02s to 0.10s, and they amplitude are respectively 20% and 15% of the fundamental wave. Compared figure 4(e), it can be known that, phase lock performance of SRF-PLL is worse than that of IDDSRF-PLL, but it is better than that of in single phase ground fault. Figure 4(f)-(h) show that, the fundamental current method can't accurately detect the harmonic current, and the other two kinds of method s can better detect the harmonic current, what's more, distortion can be extract 26.97%, 6.98% and 5.56%respectively by traditional, SRF-PLL_i_p-i_q and IDDSRF-PLL_ i_p-i_q. Obviously, in this case, traditional IDDSRF- PLL_ i_p-i_q method is better than SRF-PLL_ i_p-i_q method.

4. Conclusion

This paper briefly describes the basic principle of RF- PLL phase lock loop, and simulates the harmonic detection process of traditional, SRF-PLL_ i_p-i_q and IDDSRF-PLL_ i_p-i_q method using Matlab software and compares the simulation results. From the simulation results it can be seen that IDDSRF-PLL_ i_p-i_q method eliminates the double frequency component, restrains the influence negative sequence component brings to phase-lock link, and accurately detect the harmonic current in the grid under asymmetry and distortion circumstances; low-pass filter LPF is inserted in the phase lock link of IDDSRF-PLL_ i_p-i_q method , but there is no time-delay in the simulation results compared with other methods; Because of the integral element's use, input error of PID regulator is much smaller, but it will produce a large instantaneous pulse.IDDSRF-PLL phase lock loop brought out in this paper can not only be used in active filter detection algorithm, but also can be used in FACTS, HVDC and various power tidal current controller and other modern electric devices.

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