Research About the Positive and Negative-sequence Detection Phase-locked Loop

Jingjing Li, Renjie Zhang and Jian Zhao

ABSTRACT

Under the condition of three-phase unbalance voltages, the software phase-locked loop (SPLL) outputs an error angle which contains harmonic component due to the negative-sequence component. This paper proposes a method to remove the phase effect by eliminating negative-sequence component. This method makes a positive and negative-sequence detection for the three-phase voltage with the way of decoupling through closed loop feedback. The method is verified by an experiment which established the PLL model with Matlab. The Experiment result shows that the SPLL has a good performance in dynamic response and stability.

With the extensive use of distributed electric power generation system, the electric generator which has great power provides massive energy supply, so reliability is very important for the electric generator. Grid disturbance generator used to assess distributed electric power generation system will undergo the change from low power to high power. Typically, Grid disturbance generator with high power expands the capacity by parallel mode. For every parallel unit, it must be qualified with the ability to lock and trace the phase and frequency of fundamental wave rapidly in order to keep synchronization with the electric network.

PLL can get the phase angle of grid voltage. The basic function of PLL is to obtain the phase of positive-sequence component of three-phase voltages. If necessary, frequency and amplitude can also be acquired by PLL. All of above signals PLL got play a role in the control of power transformer, so the performance of PLL will directly affect the outputs of the power transformer.
In the SPLL, the single synchronous reference frame software PLL (SSRF SPLL) is in common use[1]. SSRF SPLL has a good effect in phase-lock under the conditions of three-phase balance voltages, but it is improper in practical use because the low bandwidth decreases the dynamic performance when three-phase unbalance voltages fault is simulated by Grid disturbance generator. In literature [2], the delay method is adopted to filter the effect of direct-current offset and negative-sequence component. But the phase-lock function of SSRF SPLL perform not constant due to the constant delay time.

To solve the synchronization problem, this paper proposes a method that bases on double synchronous reference frame PLL. Under the condition of three-phase unbalance voltages, this method can separate positive-sequence component rapidly from negative-sequence component, thus the amplitude, frequency and phase can be analyzed respectively. This method is proved by simulation of MATLAB.

ANALYSIS OF SSRF UNDER THE CONDITION OF THREE-PHASE UNBALANCE VOLTAGES

SSRF SPLL model is shown in Figure 1. The principle of operation is as follows. Three-phase voltages is decomposed into the dq rotating reference frame, the numerical value of Uq reflect the relation between axis d and voltage U. If Uq>0, that means axis d lag behind U. If Uq<0, that means U lag behind axis d. If Uq=0, that means U has the same phase with axis d. Uq represents the q axis component of grid voltage, the d axis component of grid voltage is represented by Ud. The model adopts the method of closed loop feedback, parameter PI can be used to adjust the value of Uq. When Uq=0, the output phase is synchronous with the phase of grid voltage.

Assuming that the three-phase voltage is unbalanced, the voltage can be decomposed by positive-sequence, negative-sequence and zero-sequence. Thus, three-phase voltage can be presented with the following formula

$$
\begin{bmatrix}
  u_a \\
  u_b \\
  u_c 
\end{bmatrix} =
\begin{bmatrix}
  \cos(\omega t + \phi^+1) \\
  \cos(\omega t + \phi^-1 - 120^\circ) \\
  \cos(\omega t + \phi^-1 + 120^\circ)
\end{bmatrix} +
\begin{bmatrix}
  \cos(-\omega t + \phi^-1) \\
  \cos(-\omega t + \phi^+1 - 120^\circ) \\
  \cos(-\omega t + \phi^+1 + 120^\circ)
\end{bmatrix} +
\begin{bmatrix}
  \cos(\omega t + \phi^0) \\
  \cos(\omega t + \phi^-1) \\
  \cos(\omega t + \phi^+1)
\end{bmatrix}
$$

(1)

In the formula, $U_{s^+1}$, $U_{s^-1}$, $U_{s^0}$ represent the amplitude of the voltage component of positive-sequence, negative-sequence and zero-sequence respectively; $\omega$ is the angular frequency of fundamental voltage; $\phi^+1$, $\phi^-1$, $\phi^0$ represent the initial phase angle of the voltage component of positive-sequence, negative-sequence and zero-sequence.

Based on the transformation principle of the three-phase static coordinate to the two-phase static coordinate, the voltage of two-phase static coordinate can be indicated by the following formula
\[
\begin{align*}
\mathbf{u}_{s(\alpha\beta)} &= \begin{bmatrix} u_\alpha \\ u_\beta \\ u_\gamma \end{bmatrix} = \begin{bmatrix} T_{S/2S} \\ \mathbf{U}_s \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_\gamma \end{bmatrix} \\
T_{S/2S} &= \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \\
\mathbf{u}_{s(\alpha\beta)} &= \mathbf{u}_{s(\alpha\beta)} + \mathbf{u}_{s(\alpha\beta)}^{-1} = U_s^{-1} \begin{bmatrix} \cos(\alpha \hat{\phi} + \phi_{\hat{\phi}}^{+1}) \\ \sin(\alpha \hat{\phi} + \phi_{\hat{\phi}}^{+1}) \end{bmatrix} + U_s^{-1} \begin{bmatrix} \cos(-\alpha \hat{\phi} + \phi_{\hat{\phi}}^{-1}) \\ \sin(-\alpha \hat{\phi} + \phi_{\hat{\phi}}^{-1}) \end{bmatrix} \\
U_{s(dq)}^{-1} &= \begin{bmatrix} U_{s(d)}^{-1} \\ U_{s(q)}^{-1} \end{bmatrix} = T_{dq}^{-1} \begin{bmatrix} U_{s(\alpha)} \\ U_{s(\beta)} \end{bmatrix} = U_s^{+1} \begin{bmatrix} \cos(\alpha \hat{\phi} + \phi_{\hat{\phi}}^{-1}) \\ \sin(\alpha \hat{\phi} + \phi_{\hat{\phi}}^{-1}) \end{bmatrix} + U_s^{+1} \begin{bmatrix} \cos(-\alpha \hat{\phi} + \phi_{\hat{\phi}}^{-1}) \\ \sin(-\alpha \hat{\phi} + \phi_{\hat{\phi}}^{-1}) \end{bmatrix} \\
T_{dq}^{-1} &= \begin{bmatrix} \cos \hat{\phi} & \sin \hat{\phi} \\ -\sin \hat{\phi} & \cos \hat{\phi} \end{bmatrix}
\end{align*}
\]

Figure 1. SSRF SPLL model.
According to the principle of phase-lock, we know that $\dot{\theta} = \omega t + \phi^+ - \phi^-$, so $-\omega t + \phi^- - \dot{\theta} = -2(\omega t + \phi^+) + \phi, -\omega t + \phi^- + \dot{\theta} = \phi$, $\phi = \phi^- + \phi^+$, by sorting the formula (5) and (6)

$$
\begin{bmatrix}
    u_{sn(d)}^+ \\
    u_{sn(q)}^+
\end{bmatrix} \approx U_s^+ \begin{bmatrix}
    1 \\
    \alpha t + \phi^+ + \dot{\theta}
\end{bmatrix} + U_s^+ \cos \phi \begin{bmatrix}
    \cos 2\dot{\theta} \\
    \sin 2\dot{\theta}
\end{bmatrix} + U_s^+ \sin \phi \begin{bmatrix}
    \cos 2\dot{\theta} \\
    -\sin 2\dot{\theta}
\end{bmatrix}
$$

$$
\begin{bmatrix}
    u_{sn(-d)}^- \\
    u_{sn(-q)}^-
\end{bmatrix} \approx U_s^- \begin{bmatrix}
    \cos 2\dot{\theta} \\
    \sin 2\dot{\theta}
\end{bmatrix} + U_s^- \cos \phi \begin{bmatrix}
    \cos \phi^- \\
    \sin \phi^-
\end{bmatrix}
$$

From the formula (9) and (10), the following results can be got. In the positive-sequence dq reference frame, the positive-sequence component is a DC component and the negative-sequence component is AC component with the frequency $2\omega$. In the negative-sequence dq reference frame, the negative-sequence component is DC component and the positive-sequence component is AC component with the frequency $2\omega$. From above, under the condition of three-phase unbalance voltages, SSRF SPLL has a bad performance in tracing positive-sequence component because of the effect of negative-sequence component and this makes some restrictions on SSRF SPLL.

**ANALYSIS OF THE POSITIVE AND NEGATIVE-SEQUENCE DETECTION PHASE-LOCKED LOOP UNDER THE CONDITION OF THREE-PHASE UNBALANCE VOLTAGES**

In order to achieve complete phase-lock, make the angle $\dot{\theta} = \omega t$. According to the formula (5) and (6), the voltages $U$ can be represented as below on the rotating reference frame

$$
\begin{bmatrix}
    u_{sn(d)}^+ \\
    u_{sn(q)}^+
\end{bmatrix} = U_s^+ \begin{bmatrix}
    \cos(\phi^+) \\
    \sin(\phi^-)
\end{bmatrix} + U_s^- \cos(\phi^-) \begin{bmatrix}
    \cos 2\alpha \theta \\
    -\sin 2\alpha \theta
\end{bmatrix} + U_s^+ \sin(\phi^-) \begin{bmatrix}
    \cos 2\alpha \theta \\
    \sin 2\alpha \theta
\end{bmatrix}
$$

$$
\begin{bmatrix}
    u_{sn(-d)}^- \\
    u_{sn(-q)}^-
\end{bmatrix} = U_s^- \begin{bmatrix}
    \cos(\phi^-) \\
    \sin(\phi^+)
\end{bmatrix} + U_s^+ \cos(\phi^-) \begin{bmatrix}
    \cos 2\alpha \theta \\
    \sin 2\alpha \theta
\end{bmatrix} + U_s^- \sin(\phi^-) \begin{bmatrix}
    \cos 2\alpha \theta \\
    -\sin 2\alpha \theta
\end{bmatrix}
$$

In the $d^+q^+$ reference frame, the amplitude of oscillation part is determined by the average value of $d^-q^-$ reference frame, meanwhile in the $d^-q^-$ reference frame, the amplitude of oscillation part is determined by the average value $d^+q^+$ reference frame. To restrain the oscillation part of the two reference frames, decoupling structure is used in the formula.

On the basis of formula (11) and (12), the voltage $U$ with decoupling structure can be written as follows
The decoupling part of the formula in \( d^+q^+ \) reference frame is shown in the following figure. With the same principle, the decoupling part of the formula in \( d^-q^- \) reference frame is acquired.

\[
\begin{bmatrix}
    u_s^{d+1} \\
    u_s^{q+1}
\end{bmatrix} =
\begin{bmatrix}
    u_s^{d+1} \\
    u_s^{q+1}
\end{bmatrix} - \omega_i \begin{bmatrix}
    \cos 2\alpha t \\
    -\sin 2\alpha t
\end{bmatrix} - \omega_i \begin{bmatrix}
    \sin 2\alpha t \\
    \cos 2\alpha t
\end{bmatrix}
\]

(13)

\[
\begin{bmatrix}
    u_s^{d-1} \\
    u_s^{q-1}
\end{bmatrix} =
\begin{bmatrix}
    u_s^{d-1} \\
    u_s^{q-1}
\end{bmatrix} - \omega_i \begin{bmatrix}
    \cos 2\alpha t \\
    \sin 2\alpha t
\end{bmatrix} - \omega_i \begin{bmatrix}
    -\sin 2\alpha t \\
    \cos 2\alpha t
\end{bmatrix}
\]

(14)

Figure 2. Decoupling diagram in \( d^+q^+ \) reference frame.

Figure 3. Model of positive and negative-sequence detection PLL.

To get the average value, the Low Pass Filter (LPF) is used to filter the signal with frequency \( 2\omega \). The corresponding expression is \( \text{LPF}(s) = \frac{\omega f}{s + \omega f} \).

The model of closed loop feedback PLL is show in the figure 3. From the model we draw a conclusion that the effect of three-phase unbalance voltages can be eliminated by the combination control of decoupling network and PI controller because the combination control can restrain second harmonic in \( u_{q+1} \) caused by negative-sequence component and make \( u_{q+1} \) close to zero.
MATLAB SIMULATION ANALYSIS

In order to verify the performance and possibility of positive and negative-sequence detection phase-locked loop, Matlab is used to simulate the model of this kind of PLL.

The parameters are set as follows: the amplitude of three-phase voltage is set to $U_A=1\text{pu}$, $U_B=1.3\text{pu}$, $U_C=1.3\text{pu}$, the initial phase of voltage A is zero and the frequency is 50Hz; in the PI controller, parameter $kp=180$ and $ki=22500$; the cut-off frequency $\omega_f$ of LPF is 157rad/s.

The simulation result of positive and negative-sequence detection PLL is shown in Figure 4. Amplitude of the phase A voltage is lower than the amplitude of phase B voltage and phase C voltage. The wave shape of the signal made by this kind PLL is consistent with the wave shape of phase A voltage. This shows that the effect of

![Figure 4](image)

Figure 4. Waveshape of three phase input voltage and output signal under the condition of three-phase unbalance voltages.

![Figure 5](image)

Figure 5. The amplitude waveshape of positive-sequence component $U_q^+$.  

![Figure 6](image)

Figure 6. Amplitude waveshape under the condition of voltage distortion.

negative-sequence component under the condition of three-phase unbalance voltages is eliminated by positive and negative sequence decoupling. The conclusion that positive and negative-sequence detection PLL can trace the phase of positive-sequence component under the condition of three-phase balance voltages is also validated.
The amplitude waveshape of positive-sequence $U_q$ produced by phase detector is shown in figure 5. The dynamic response of phase detector can be used to estimate the dynamic performance of the PLL. The following result is got from the simulation. Under the control of PI controller, the max variance of $U_q$ is 0.32. After two period adjustment, the max variance of $U_q$ become 0 and keep it since then. From above, the conclusion that the dynamic response of positive and negative-sequence detection phase-locked loop perform well is drawn.

If harmonic wave is filled in the phase A voltage, the amplitude waveshape of phase A voltage become distorted. The simulation result shows that although the amplitude waveshape of phase A voltage become distorted, the phase of output signal can totally lock the phase of the positive-sequence component of phase A voltage.

Figure 7 is the phase waveshape under the condition of voltage distortion and this phase waveshape is produced by positive and negative-sequence detection phase-locked loop. The figure shows that the PLL go through the process of adjustment at the first period and the change of phase is not linear. At the time of 0.02s, the phase only has little difference with the max value. This kind of PLL can lock the phase accurately at the end of the second period. The adjustment time is only two periods, so the conclusion that positive and negative-sequence detection phase-locked loop has good performance in stability and dynamic response under the condition of voltage distortion.

CONCLUSIONS

The positive and negative-sequence detection phase-locked loop is designed to solve the problem of phase-lock inaccurate under the condition of three-phase unbalance voltages. The simulation results show that the positive and negative-sequence detection phase-locked loop has a good performance in dynamic response and stability and it can restrain the effect of three-phase unbalance voltages effectively.

REFERENCES

1. S.K. Chung, A phase tracking system for three phase utility interface inverters, IEEE Transactions on Power Electronics, 2000, 15(3): 431-438.
2. R.K. Sinha, P.S. Sensarma, Improved PLL under distorted utility conditions, IEEE International Conference on Industrial Technology, 2006: 1849-1854.