A Terminal Voltage Estimation and Unbalance Compensation Strategy Based on Double Synchronous Reference Frame for Shore Power Supply

Qian Cheng* and Xiaochun Mou
NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing 211000, China

*Corresponding author e-mail: chengqian@sgepri.sgcc.com.cn

Abstract. In this paper, a strategy of terminal voltage estimation unbalance compensation for shore power supply is proposed. In this strategy, based on double synchronous reference frame, sequence components are extracted from the measured current and voltage fast and precisely. And then, the terminal voltage could be accurately estimated under the equivalent circuit in the form of vector. At last, a simple and robust method is applied for voltage compensation, from which independent adjustability on the magnitude and the phase of both positive and negative sequence of terminal voltage can be achieved. The proposed strategy is simulated in PSCAD. The simulation results show that, by this strategy, the terminal voltage can be rapidly compensated to be fully balanced and adjusted to the demanded phase within 15ms.

1. Introduction
A typical arrangement of a frequency-converter-type shore power supply is illustrated in Fig.1. Grid voltage is inverted into specific frequency and voltage by a back-to-back converter. A filter is adopted to get the sine-wave voltage. A transformer is necessary not only for stepping the voltage but also for the purpose of isolation. At last, the processed voltage is transferred to ship load through a long cable.

The quality of the shore power supply's output voltage is influenced by the load. The unbalanced voltage caused by the unbalanced load current would bring harm to the ship's equipment, such as the vibration of the rotating machines. In [1, 2], a fourth leg is added so that the neutral point current can be controlled to get the balanced output voltage. In [3, 4], the unbalanced part of the load current is provided

![Figure 1. Typical arrangement of shore power supply.](image-url)
by a compensation device connected in parallel at the output terminal, leaving the balanced part to the voltage source. However, these above mentioned methods need extra hardware, which means more cost, area occupied and complexity. In [5], the repetitive control is introduced in a three-phase UPS and the anti-unbalance performance is quite satisfactory. But compared with UPS, the converter of the shore power supply has a much lower switching frequency, at which the repetitive control might not be applicable. In [6, 7], advanced regulation methods based on state space are proposed. However, the parameter tuning of these methods are not intuitive. Besides, massive matrix computation is still a big burden for a normal DSP. The unbalance compensation strategy described in this paper is based on double synchronous reference frame. The negative component is removed by setting its reference value to be 0 in the closed loop. At last, no more hardware or measurement is needed to implement this strategy.

2. Sequence components decomposition

Unbalanced voltage (or current) can be decomposed into positive, negative and zero sequence components [8]. According to [9], the recommended configuration of the isolation transformer is Δyn. Due to this configuration, zero sequence components are not taken into consideration. A set of three-phase voltages, \( u_a \), \( u_b \) and \( u_c \), can be treated as the superposition of the positive and the negative sequence components, which are expressed as (1) and (2) respectively.

\[
\begin{align*}
    u_a^+ &= U^+ \cos(\omega t + \psi^+) \\
    u_b^+ &= U^+ \cos\left(\omega t - \frac{2\pi}{3} + \psi^+\right) \\
    u_c^+ &= U^+ \cos\left(\omega t + \frac{2\pi}{3} + \psi^+\right) \\
    u_a^- &= U^- \cos(\omega t + \psi^-) \\
    u_b^- &= U^- \cos(\omega t + \frac{2\pi}{3} + \psi^-) \\
    u_c^- &= U^- \cos(\omega t - \frac{2\pi}{3} + \psi^-)
\end{align*}
\]

(1)

The Clarke transformation is made for the original three-phase voltage \( u_a \), \( u_b \) and \( u_c \), as (3), resulting in a vector \( \vec{u} \) in \( \alpha \beta \) coordinate, which is a stationary reference frame. From (3), it can be clearly shown that \( \vec{u} \) is composed of two independent vectors, \( \vec{u}^+ \) and \( \vec{u}^- \). The prior one rotates anticlockwise while the other one rotates in the opposite direction.

\[
\begin{bmatrix}
    u_a^+ \\
    u_b^+ \\
    u_c^+
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & \frac{1}{2} & \frac{1}{2} \\
    \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
    \frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
    u_a \\
    u_b \\
    u_c
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
    1 & \frac{1}{2} & \frac{1}{2} \\
    \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
    \frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
    u_a^+ + u_a^- \\
    u_b^+ + u_b^- \\
    u_c^+ + u_c^-
\end{bmatrix}
\]

(3)

Two rotating coordinates are defined, \( d^+q^+ \) and \( d^-q^- \), whose angular speeds are \( \omega t \) and \( -\omega t \) respectively. As shown in Fig. 2, the \( d \) axes of the two coordinates are symmetrical with respect to the \( \alpha \) axes and have an angle shift of \( \theta \). As the positive sequence voltage vector \( \vec{u}^+ \) has the same speed with the \( d^+q^+ \) coordinate, its projections (\( u_d^+ \) and \( u_q^+ \)) on \( d^+ \) and \( q^+ \) axes keep constant, in steady state. The same do the negative sequence voltage vector \( \vec{u}^- \) and the \( d^-q^- \) coordinate. However, it is infeasible to separate \( \vec{u}^+ \) and \( \vec{u}^- \) directly from \( \vec{u} \). Based on Fig.2 and the result of (3), if letting \( \theta = \omega t \), the projections of \( \vec{u} \) on \( d^+ \), \( q^+ \), \( d^- \) and \( q^- \) axes can be calculated as shown in (4) and (5).
From the above derivation, it is not difficult to find that \( \tilde{U}_d^+ \), the instantaneous value of the projections of \( \tilde{U} \) on \( d^+ \) axes, is made up of one steady item and two oscillated items. The steady item \( u_q^+ \) is the projection of \( \tilde{U} \) on \( d^+ \) axes, which is sought so far. So the intuitive method of getting \( u_q^+ \) is to put a low-pass filter behind \( \tilde{U}_d^+ \) to remove the two oscillated items. \( u_q^- \), \( u_q^+ \) and \( u_q^- \) can be extracted in the same way. However, it is a tricky problem to select the bandwidth of this low-pass filter in order to get a balance between attenuation and convergence speed \[10\]. So to accelerate the convergence speed of the low-pass filter, a decoupling network is applied to cancel out the oscillated items roughly. A block diagram that sums up the procedure described above is illustrated in Fig.3.

![Figure 2. Reference frames and voltage vectors](image)

![Figure 3. Block diagram of sequence components decomposition](image)

Based on the conclusion in \[10\], if the cutoff frequency \( \omega_c \) of the low-pass filter is set to \( \omega/\sqrt{2} \), the estimated quantities (\( u_a^+, u_b^+, u_c^- \) and \( u_d^- \)) will approach to their final value (\( u_a^-, u_b^-, u_c^- \) and \( u_d^- \)) in the shortest time without any overshoot. Three choices of cut-off frequency \( f_c \), 20Hz, 40Hz and 60Hz, are verified by simulation. Among them, 40Hz is very close to 42.43Hz, which is \( 1/\sqrt{2} \) times of the base frequency of 60Hz. The unbalanced voltage is constructed by given \( u_a^+, u_b^-, u_c^- \) and \( u_d^- \), through inverse Park transformation, vector superposition and two-to-three transformation. Then the artificial
voltages are sent to the corresponding inputs of the structure shown in Fig.4. The step responses under different cut-off frequency for each sequence are plotted in the same subfigure of Fig.4.

![Figure 4. Performance evaluation of sequence components decomposition](image)

From the simulation result, it is obvious that the step response when $f_c$ being 20Hz is much slower than when $f_c$ being 40Hz or 60Hz. The overshoot of the step response when $f_c$ being 60Hz is nearly 60%, which might lead to instability when the voltage closed loop is introduced in later. It is noticed that there still exists 20% overshoot if the cut-off frequency is set to be 40Hz, which differs from the conclusion in [10]. The reason causing this difference is that in [10] the negative sequence takes a step change while the positive sequence keeps constant, which makes that conclusion established. However, this 20% overshoot is acceptable since fast sequence decomposition is the primary task.

3. Voltage Estimation
To demonstrate how the voltage of ship-side terminal is accurately estimated using equivalent circuit, the configuration of a practical 1MVA shore power supply project is employed. The arrangement of devices of this project is the same as Fig.1. The topology of the sine-wave filter and the main parameters of each device are illustrated in Fig.5 and Table 1.
**Table 1. Parameters of devices concerned**

|                  | Converter |                  |                  |                  |                  |                  |
|------------------|-----------|------------------|------------------|------------------|------------------|------------------|
| Rated power      | 1MVA      | Rated voltage of ship side | 600V             |                  |                  |                  |
| Rated voltage of grid side | 690V      | Rated frequency of ship side | 60Hz             |                  |                  |                  |
| Rated frequency of grid side | 50Hz      | Switching Frequency | 2.5kHz           |                  |                  |                  |
| Sine-Wave Filter |           |                  |                  |                  |                  |                  |
| $L_m$            | 220μH     | $R_1$            | 0.5Ω             |                  |                  |                  |
| $L_1$            | 160μH     | $C_2$            | 240μF            |                  |                  |                  |
| $C_1$            | 25μF      | $R_2$            | 0.25Ω            |                  |                  |                  |
| Transformer      |           |                  |                  |                  |                  |                  |
| Rated power      | 1MVA      | Winding of primary side | $\Delta$        |                  |                  |                  |
| Base Frequency   | 60Hz      | Winding of secondary side | $Y$             |                  |                  |                  |
| Rated voltage of primary side | 600V    | $\Delta$ lags or leads $Y$ | Lags            |                  |                  |                  |
| Rated voltage of secondary side | 6600V | Leakage reactance | 0.06p.u.       |                  |                  |                  |
| Cable            |           |                  |                  |                  |                  |                  |
| Core cross section | 3×50mm$^2$ | Resistance at 90°C | 0.499Ω/km       |                  |                  |                  |
| Core material    | Copper    | Inductance       | 0.355mH/km      |                  |                  |                  |
| Nominal Voltage Uo/U | 6/10kV    | Capacitance per phase | 300nF/km       |                  |                  |                  |
| Resistance at 20°C | 0.391Ω/km | Length            | 1.5km           |                  |                  |                  |

As the exist of DC-link capacitor, the two sides of converter are fully decoupled. Besides, DC-link voltage is regulated to 1100V, being high enough relative to the rated voltage of ship side, which means that the over modulation barely happens. Based on the above facts, within specific voltage range, the ship side of the converter could be treated as an ideal arbitrary voltage generator. In the circumstance that the sequence components are expressed in the form of ‘vector’, two rules should be kept. The one is that when calculating the impedance of the inductor or the capacitor, use $2\pi f$ for positive sequence and $-2\pi f$ for negative sequence. The other one is that the phase shift of the transformer remains the same for both positive and negative sequence. Note that, the above two rules are not applicable if sequence components are expressed in the form of ‘phasor’.

According to the rating value listed in Table 1, the equivalent circuit of filter, transformer and cable in per-unit system can be derived as Fig.6. This equivalent circuit fits both positive and negative sequence. The two bypass branches of the sine-wave filter are merged as one with impedance of $Z_b$. The transformer is simplified as a leakage reactance followed by an ideal 1:1 transformer with phase shift of $30^\circ$. At last, the cable is treated as a series impedance while the shunt impedance is neglected.

![Figure 5. The topology of the sine-wave filter](image)

![Figure 6. The equivalent circuit from converter to ship-side terminal.](image)

The per-unit values of $Z_{lm}$, $Z_b$, $Z_{leak}$ and $Z_{cable}$ for positive sequence and negative sequence are listed in Table 2.
Table 2. Per-unit value of impedance

|          | $Z_{lm}$ | $Z_b$           | $Z_{leak}$ | $Z_{cable}$ |
|----------|----------|-----------------|------------|-------------|
| Positive | 0.2304   | 0.5819-i27.804 | 0.06       | 0.0153-i0.0046 |
| Negative | -0.2304  | 0.5819+i27.804 | -0.06      | 0.0153-i0.0046 |

Two sets of quantities are measured by Hall transducers. One set is the three-phase converter current, $i_{\text{con}}$, which takes ’running into converter’ as the positive direction. The other one is the output voltage of the sine-wave filter, $u_{o1}$, which is also the voltage of the transformer's primary side. Using the strategy introduced in Section 2, the positive and negative sequence vectors $\tilde{i}_{\text{con}}^+$, $\tilde{i}_{\text{con}}^-$, $\tilde{u}_{o1}^+$, and $\tilde{u}_{o1}^-$, can be decomposed from the measured voltage and current. From Fig.6, the positive and negative sequence vector of ship-side terminal voltage could be estimated as:

\[
\hat{u}_{o2}^+ = \left[ \left( \tilde{i}_{\text{con}}^+ + \frac{u_{o1}^+}{Z_b} \right) (Z_{\text{leak}} + Z_{\text{cable}}) + \tilde{u}_{o1}^+ \right] e^{j30^\circ} \tag{6}
\]

\[
\hat{u}_{o2}^- = \left[ \left( \tilde{i}_{\text{con}}^- + \frac{u_{o1}^-}{Z_b} \right) (Z_{\text{leak}} + Z_{\text{cable}}) + \tilde{u}_{o1}^- \right] e^{j30^\circ} \tag{7}
\]

To verify the estimation result, the three-phase voltage of ship-side terminal could be reconstructed by series of transformation. In PSCAD, it is easy to compare the reconstructed voltages with the real ones simultaneously. In simulation, the load is simplified as serial RL in Y connection. The changing pattern of $R_{a(b,c)}$ and $L_{a(b,c)}$ is illustrated in Fig.7. To observe the influence of the load change on terminal voltage, the magnitude, the frequency and the phase of the converter's output voltage keep constant.

![Figure 7. Load changing pattern](image)

In Fig.8, the real line voltages and the reconstructed ones are plotted in pair. From the simulation result, it can be clearly shown that the waveforms of the reconstructed voltage almost overlap the ones of real voltage totally. Slight difference occurs in transition stage of the load and the reconstructed voltages lose some details of transient process that the real voltages have. The difference is caused by the low-pass filters applied in positive and negative sequence decomposition which remove the transient information of the measured voltage and current. This is also the reason why the reconstructed voltages are much smoother than the real ones.
4. Voltage Regulation

From the comparison of reconstructed and real ship-terminal voltage, it is considered to be feasible that the estimated sequence components $\hat{u}_{02}$ and $\hat{u}_{02}$ are used in closed-loop voltage regulation to replace real ones. To get satisfactory voltage regulating effect, a large gain is desired for the close-loop controller [12]. However, a large gain might lead to an overvoltage in some conditions, for example, the measuring or sampling disturbance. Hence, a hybrid controller structure that contains feedback and feed forward is adopted. The controller structure is shown in detail as Fig.9.

![Diagram of the proposed controller structure](image)

Figure 9. The diagram of the proposed controller structure

D and q components of ship-side terminal voltage's positive and negative are regulated separately. The reference voltage is passed forward straightly as base, to maintain the controlled voltage within reasonable range. The PI controller generates a bias based on the error between the reference and
estimated voltage, to counteract the voltage deviation caused by the load change. As the transformer contribute a fixed voltage phase shift from the converter to the ship-side terminal, the regulating voltage of the converter is lagged $30^\circ$ from the output of PI controller. Then, the calculated regulating voltage is transferred from rotating coordinates to stationary coordinates using $\omega t$ and $-\omega t$ respectively. At last, the superposed voltage vector, as well as instantaneous DC-link voltage, are sent to the SVPWM module to get the duty cycle of each bridge arm.

Let $K_p = 1$ and $K_i = 100$ for each PI controller in Fig. 9. Fig. 10 (b) shows the three-phase ship-side terminal voltages when the same load changing pattern as Figure 7 is applied. For comparison, the unbalanced terminal voltages, under the condition that voltage is generated in an open-loop way, are also plotted in Fig. 10 (a). From these two plots, it is evident that the above mentioned voltage regulation strategy does suppress the voltage unbalance caused by the nonsymmetrical load. However, it is noticed that this regulation strategy does not improve the wave distortion at the moment of load change. The reason is that the dynamic process of the positive and negative components extraction is relatively slow compared with that of the main circuit.

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The voltage estimation and regulation methods introduced in this paper can also be used to adjust the phase of the output voltage by changing the relation between $u_{dref}^+$ and $u_{qref}^+$. For instance, if a phase shift of $+90^\circ$ is required, just switch the set-point values of $u_{dref}^+$ and $u_{qref}^+$. Fig. 11 (a) and Fig. 11(b) show the phase shift process after that the $+90^\circ$ phase shift command is set to the voltage regulator at $t = 0.5s$. It cost less than one circle time to accomplish a phase shift of $+90^\circ$, which would be very useful when synchronization between shore power supply and ship's own generator is needed [13].
5. Conclusion
This paper presents an estimation method for the terminal voltage based on double synchronous reference frame. Comparison shows that the estimated terminal voltages are accurate enough to replace the real ones, which results in the elimination of high voltage transducer and long distance sampling data transmission. Then a hybrid structure of voltage regulation is proposed. Simulation results show that this hybrid-structure voltage regulator along with the estimated terminal voltages can magnificently compensate the unbalanced terminal voltages caused by the unbalanced load. Besides, the phase of the terminal voltage can be easily adjusted by changing the set point of the voltage regulator.

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