Dynamic State Estimation Enabled Predictive Inverter Control

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Abstract—High penetration of Converter-Interfaced Generation (CIG) presents challenges because there exists no or very little mechanical coupling between CIGs and the power grid. During transients, the operational constraints of the inverters may be exceeded to the point of damaging the inverters or causing the shutdown of the inverters (LVRT logic). This paper proposes a Dynamic State Estimation (DSE) enabled supplementary predictive inverter control scheme to minimize the transients during grid disturbances. This control scheme only uses local information and does not require any communication from the system (remote) side. We first estimate frequency as well as rate of frequency change of the remote side with only local information via DSE, which uses high-fidelity dynamic model of the interested component to provide accurate feedback to the inverter controls. Second, a supplementary predictive inverter control scheme is utilized to control the output frequency, real power as well as the reactive power of the grid-side inverter. Numerical simulations show that the proposed DSE method can accurately estimate remote side frequency as well as rate of frequency change. Additionally, the proposed control scheme can successfully minimize transients during system frequency oscillations.

Key words—Converter Interfaced Generation (CIG), Dynamic State Estimation (DSE), predictive inverter control, local information

1 INTRODUCTION

There is an increasing penetration of generating units that are interfaced to power grid with power electronic devices [1]. The system allows the generating units to operate at variable or non-synchronous frequencies (e.g. wind turbines), or to operate without any rotating parts (e.g. photovoltaic cells). On the other hand, these generating units are usually connected to a system with a fixed frequency via converter interfaces. These generating units are referred as Converter-Interfaced Generations (CIGs). Nowadays the power system can easily cope with a small amount of CIGs. However, in some areas (locally) the power fed by CIGs may rise and rapidly reach 100% penetration, which will bring additional challenges to present control paradigm. Detail discussions are provided as follows.

The conventional power system powered by synchronous generators has the following characteristics. (a) synchronous generators are driven by mechanical torque, so the control of the speed governor can maintain load/generation balance by controlling the frequency of the synchronous generator; (b) synchronous generators have high moment of inertia, so the oscillations of frequency and phase angle are small and slow, and transient stability of the power system can be ensured.

Compared to the conventional power system, a power system with high penetration of CIGs will confront the following challenges. (a) There exists no mechanical torque input to the DC link of a grid side converter, thus the control of the converter output frequency is irrelevant to load/generation balancing [2-3]. That results in failures of traditional control schemes, such as using area control error (ACE) to control the frequency of the system. (b) CIGs originally do not have inertia [4-5], thus the frequency and phase angle may oscillate quickly after disturbances and in this case the operational constraints of the inverters may be exceeded to the point of damaging the inverters or causing the shutdown of the inverters (LVRT logic).

One existing approach to deal with these issues is to control the converter interface such that the CIG systems behave similarly as synchronous machines with frequency responses and inertia [6-7]. However, this approach may not as good as expected because synchronizing torques are contributed by high transient currents during disturbances. For traditional power systems, synchronous machines can provide transient currents in the order of 500% to 1000% of load currents. On the contrary, the converters have to limit the transient currents to no more than approximately 200% of load currents and further decrease this value as time evolves [8], which lasts for an even shorter period of time than synchronous machines. Consequently, the CIGs’ imitation of synchronous machines might not be quite effective.

The present technologies to control a grid-side converter based on local information are categorized into two groups: two axis and three axis based converter controls with a constant frequency [9-11]. Two axis based converter control includes dq and αβ frame based two stage closed loop controls. The three axis based converter control is an abc frame based two stage closed loop control. The main disadvantages are as follows: (a) the two axis-based converter controls with a constant frequency cannot guarantee the stability and high power quality of a power system when the frequency change of the remote site is fast and large; (b) for the three axes-based converter control, the switching frequency of the hysteresis control cannot be determined and controllable so it requires additional control loops.

![Figure 1: An example system using DSE with local information](image-url)
To control the CIGs such that the CIG smoothly follows the oscillations of the system and avoids excessive transients, a Dynamic State Estimation (DSE) enabled supplementary predictive inverter control (P-Q mode) scheme is proposed. An example system is provided in Figure 1, where a Wind Turbine System (WTS) is connected to a transmission line via a transformer, and only inverter (local) side three-phase voltage and current measurements are available. The method only needs local side information and no communication from the system (remote) side is required. The method consists of the following two steps.

(a) We first calculate remote side frequency as well as rate of frequency change by estimating remote side instantaneous voltages and currents from the DSE method [12-14] with only local information. This proposed DSE method estimates the states of the interested component from instantaneous measurements and the dynamic model. The dynamic model describes all the physical laws that the component must obey. It utilizes realistic models of the component instead of sequence parameters, so it can precisely capture the performances of the component during transients and disturbances. This method is much more accurate compared to methods based on phasors where voltages and currents are assumed as pure sinusoidal waveforms with fixed synchronous frequency.

(b) The remote side frequency as well as rate of frequency change are afterwards used as inputs to the proposed controller. The controller mainly contains three control loops to control the output frequency, the real power as well as the reactive power of the grid-side inverter.

In this paper, we first describe the method to estimate remote side frequency as well as rate of frequency change with only local information by DSE. Next, the supplementary predictive inverter control scheme with estimated remote side frequency information is introduced in detail. Finally, the effectiveness of proposed DSE algorithm as well as our proposed control scheme is evaluated via numerical simulations.

II REMOTE SIDE FREQUENCY INFORMATION ESTIMATION WITH ONLY LOCAL INFORMATION BY DSE

This section presents the technology to estimate the frequency as well as rate of frequency change at the system (remote) side with local measurements only. The estimated frequency and the rate of frequency change will be afterwards used to provide feedback to inverter controls. To achieve this estimation, Dynamic State Estimation (DSE) method is utilized. The method estimates the states of the transmission line that connects the CIG and the power system by solving a set of equations described by the measurement dynamic model of the interested component. After that, voltages and currents at the remote side can be calculated from the estimated states of the line, and frequency information can be calculated. Details of the DSE method are discussed as follows: (a) dynamic model of the component; (b) dynamic state estimation process.

A. Dynamic Model of the Component

The dynamic model of the interested component describes all the physical laws that the component should satisfy, which usually consists of several algebraic/differential equations. In general, dynamic models of different kinds of components can be written with the same device Quadratized Dynamic Model (QDM) as shown in equation (1), where all the nonlinearities are reduced to no more than second order by introducing additional variables if necessary. The measurement QDM is obtained after selecting specific rows of equations corresponding to the available measurements. The QDM syntax is as follows,

Device QDM:

\[
i(t) = Y_{eq1} x(t) + D_{eq1} \frac{dx(t)}{dt} + C_{eq1}
\]
\[
0 = Y_{eq2} x(t) + D_{eq2} \frac{dx(t)}{dt} + C_{eq2} \tag{1}
\]
\[
0 = Y_{eq3} x(t) + \left\{ x(t)^T \! \left( F_{eq1} \! \right) x(t) \right\} + C_{eq3}
\]

Measurements QDM:

\[
z(x) = Y_{quan,x} x(t) + \left\{ x(t)^T \! \left( F_{quant} \! \right) x(t) \right\} + D_{quant} \frac{dx(t)}{dt} + C_{quan} \tag{2}
\]

where \(i(t)\) is the through variables (terminal currents); \(x(t)\) is the state variables, \(z(t)\) is the measurements, and others are parameter matrices and vectors of the interested component.

For this case a multi-section transmission line model is established, where each section consists of a lumped \(\pi\)-equivalent model and the length of each section is the same. Detail device QDM for the lumped \(\pi\)-equivalent model of each section is provided in Appendix A. The total number of section is chosen in such a way that the traveling length of the electromagnetic wave during one sampling interval is comparable to the length of each section. The method to combine the QDM for each section into one multi-section QDM is to add additional equations that describes (1) the voltage states between two consecutive sections are the same; (2) the sum of currents flowing into one node between two consecutive sections is zero.

B. Dynamic State Estimation Process

There are several ways to solve the states of the component from QDM. In this paper, we only introduce one of the most common ways, which is to convert QDM into another standard syntax Algebraic Quadratic Companion Form (AQCF) through quadratic integration method [15] and form an optimization problem via Weighted Least Squares (WLS). The AQCF syntax is described as follows,

Device AQCF:

\[
\begin{bmatrix}
i(t) \\
0 \\
0 \\
i(t_m)
\end{bmatrix} = Y_{aq1} \begin{bmatrix} x(t,t_m) \\
\dot{x}(t,t_m) \\
\ddot{x}(t,t_m)
\end{bmatrix} + \left\{ x(t,t_m)^T \! \left( F_{aq1} \! \right) x(t,t_m) \right\} + b(t-h) \tag{3}
\]

2
Measurement AQCF:

\[ z(x) = Y_m x(t, t_{m}) + \left( x(t, t_{m})^{-T} \left( F_{m, e} \right) x(t, t_{m}) \right) + b_m (t-h) \]  \hspace{1cm} (4)

where \( t_m = t - h/2 \), and \( h \) is the DSE calculate step. Other definitions are similar as in QDM.

The states of the interested component can be obtained by solving the WLS problem. The results of the states are given with the following iterative algorithm:

\[ x(t, t_{m})^{y+1} = x(t, t_{m})^{y} - \left( H^T WH \right)^{-1} H^T W \cdots \]

\[ Y_{eq} x(t, t_{m}) + \left( x(t, t_{m})^{-T} \left( F_{eq} \right) x(t, t_{m}) \right) + b \left( t-h \right) - z \]

where \( W = \text{diag} \left\{ \sigma_1^2, \ldots, \sigma_n^2 \right\} \) is the standard deviation of the measurement error, and \( H \) is the Jacobean matrix:

\[ H = Y_m + \left( x(t, t_{m})^{-T} \right) F_{m, e} + F_{m, e} \left( x(t, t_{m})^{-T} \right) \]

\[ \text{III Supplementary Predictive Inverter Control from Estimated Remote Side Frequency Information} \]

This part presents the supplementary predictive inverter control (P-Q mode) of the switching signal generator, after obtaining the estimated remote side frequency \( f_{\text{remote}}(t_k) \) as well as rate of frequency change \( df_{\text{remote}}(t_k)/dt \) from local information only. The diagram of supplementary predictive control is shown in Figure 2.

The diagram consists of the following two control parts: (a) frequency modulation control; (b) modulation index and phase angle modulation control. After the above two control parts, three control signal outputs \( f_{\text{outl}}(t_{k+1}) \), \( \theta_{\text{cnrl}}(t_{k+1}) \) and \( m_{\text{cnrl}}(t_{k+1}) \) are obtained to generate switching sequences and control the inverter with expected output voltage frequency, phase angle and amplitude. Details of the two control schemes will be introduced next.

\[ \Delta \delta_{\text{local}}(t_{k+1}) = 2\pi \left( f_{\text{local}}(t_k) \cdot h + \frac{df_{\text{local}}(t_k)}{dt} \cdot h^2 \right) \]

(7)

\[ \Delta \delta_{\text{remote}}(t_{k+1}) = 2\pi \left( f_{\text{remote}}(t_k) \cdot h + \frac{df_{\text{remote}}(t_k)}{dt} \cdot h^2 \right) \]

(8)

\[ h = t_{k+1} - t_k \]

(9)

where \( t_k \) and \( t_{k+1} \) are the time of this step and next step: \( f_{\text{local}} \), \( df_{\text{local}}/dt \), \( f_{\text{remote}} \), and \( df_{\text{remote}}/dt \) are the frequency and the rate of frequency change at the local and the remote side.

Next, a closed-loop feedforward control is implemented to generate the frequency modulation control command.

\[ X(t_{k+1}) = \left( \Delta \delta_{\text{remote}}(t_{k+1}) - \Delta \delta_{\text{local}}(t_{k+1}) \right) \]

\[ + \left( \Delta \delta_{\text{remote}}(t_{k+1}) - \Delta \delta_{\text{local}}(t_{k+1}) \right) + \Delta \delta_{\text{local}}(t_{k+1}) \cdot h \]

\[ X(t_{k+1}) = -K_{\text{PFM}} \cdot X(t_{k+1}) + \frac{1}{K_{\text{PFM}}} \cdot f_{\text{local}}(t_{k+1}) \]

(10)

(11)

where \( K_{\text{PFM}} \) and \( K_{\text{IPM}} \) are the proportional and the integral coefficient of frequency modulation control.

\[ \text{B. Modulation Index and Phase Angle Modulation Control} \]

The purpose of this control part is to provide a constant real and reactive power output according to the given real and reactive power references. The real power flow can be controlled through the phase angle difference between the local side and the remote side, or in this case the local side phase angle \( \theta_{\text{cnrl}} \). A proportional and integral (PI) control based real power control scheme is developed as follows,

\[ X(t_{k+1}) = P_{\text{ref}}(t_{k+1}) - P_{\text{ref}}(t_k) \]

\[ + \left( P_{\text{ref}}(t_{k+1}) - P_{\text{ref}}(t_{k+1}) - P_{\text{ref}}(t_k) \right) \cdot h \]

\[ X(t_{k+1}) = -K_{\text{PP}} \cdot X(t_{k+1}) + \frac{1}{K_{\text{PP}}} \cdot \theta_{\text{cnrl}}(t_{k+1}) \]

(13)

(14)

\[ -\frac{\pi}{2} \leq \theta_{\text{cnrl}}(t_{k+1}) \leq \frac{\pi}{2} \]

(15)

where \( P_{\text{ref}} \) and \( P_{\text{ref}} \) are measured and reference real power, and \( K_{\text{PP}} \) and \( K_{\text{IP}} \) are the proportional and the integral coefficient of real power (phase angle modulation control).
The reactive power flow can be controlled through the output voltage amplitude of the inverter, or in this case the modulation index \( m_{\text{mod}} \) of the SPWM of the switching signal generator. A proportional and integral (PI) control based reactive power control scheme is developed as follows,

\[
X(t_{i+1}) = (Q_m(t_{i+1}) - Q_m(t_i)) + (Q_m(t_{i+1}) - Q_m(t_i)) h
\]

\[
\hat{X}(t_{i+1}) = \frac{K_P}{K_Q} X(t_{i+1}) + \frac{1}{K_Q} m_{\text{mod}}(t_{i+1})
\]

where \( Q_m \) and \( Q_{\text{ref}} \) are measured and reference reactive power, and \( K_Q \) and \( K_P \) are the proportional and the integral coefficient of reactive power (modulation index) control.

IV ILLUSTRATIVE RESULTS

An example test system has been used to illustrate the performances of the proposed DSE algorithm as well as the control scheme. The example system and simulation results are as follows.

A. System Configuration

An example test system with 60 Hz synchronous frequency is provided in Figure 3. It consists of a wind turbine system (WTS) with a 50 Hz voltage input. The wind turbines are connected to a 1.5-mile 34.5kV transmission line via two converters and a 690V:34.5kV transformer. On the other side, the disturbance is simulated by an oscillating source with frequency 60 ± 0.1 Hz (with oscillating rate 1 Hz), connected to the system via a 1.5-mile 115kV transmission line and two transformers (15kV:115kV and 34.5kV:115kV). Three phase current and voltage measurements are installed locally near WTS, at bus S of the 34.5kV transmission line L-R.

Figure 4 shows the results of the frequency and rate of frequency change at the remote side of the line. In the first two channels we have instantaneous values of three phase actual voltages and DSE estimated voltages. In the third and fourth channel the actual and estimated frequency are compared and we can observe that the maximum absolute error is quite small (0.177 milli-Hz). In the fifth and sixth channel, the actual and estimated rates of frequency change are compared and similarly we have a very small absolute error of the estimation (1.144 milli-Hz/s).
compared to traditional control schemes, which implies tiny transients during disturbances.

V CONCLUSIONS

High penetration of Converter Interfaced Generation (CIG) brings challenges to the inverter control during transients. The operational constraints of the inverters may be exceeded to the point of damaging the inverters or causing the shutdown of the inverters. The paper proposed a new Dynamic State Estimation (DSE) enabled supplementary predictive inverter control scheme using local information only. It first estimates remote side frequency as well as rate of frequency change via DSE, to provide feedback to the inverter controls. Next, the proposed supplementary predictive inverter control scheme is used to minimize the transients during disturbances. Numerical simulations prove that the proposed control scheme can:

(a) work without any communication from the system side;
(b) accurately estimate remote side frequency as well as rate of frequency change by DSE;
(c) strongly reduce transients during frequency oscillations of the system compared to traditional control schemes.

VI ACKNOWLEDGMENT

This work is supported by PSERC projects S-56 and T-55G. This support is greatly appreciated.

VII REFERENCES


VIII APPENDIX A

This Appendix describes the QDM of a lumped \( \pi \)-equivalent transmission line. The equivalent circuit of the line is provided in Figure A-1.

Figure A-1. Equivalent Circuit of a Lumped \( \pi \)-equivalent Transmission Line

The standard format of QDM is given in equation (1), part II. The QDM parameters for this model are:

\[
i(t) = \begin{bmatrix} i_1(t) & i_2(t) \end{bmatrix}^T; \quad x(t) = \begin{bmatrix} v_1(t) & v_2(t) & i_3(t) \end{bmatrix}^T;
\]

\[
Y_{eq1} = \begin{bmatrix} 0 & 0 & I_4 \\ 0 & 0 & -I_4 \end{bmatrix}; \quad D_{eq1} = \begin{bmatrix} C & 0 & 0 \\ 0 & C & 0 \end{bmatrix}; \quad C_{eq1} = 0;
\]

\[
Y_{eq2} = \begin{bmatrix} -I_4 & I_4 & R \end{bmatrix}; \quad D_{eq2} = \begin{bmatrix} 0 & 0 & L \end{bmatrix}; \quad C_{eq2} = 0;
\]

equation all other vectors and matrices are null; and, \( R, L, \) and \( C \) are the resistance, inductance and capacitance matrices of the equivalent circuit; \( i_1(t) \) and \( i_2(t) \) are current vectors at each side; \( v_1(t) \) and \( v_2(t) \) are voltage vectors at each side; \( i_3(t) \) is the current vector of the inductance; \( I_4 \) is the identity matrix with dimension 4.

![Figure A-1](image_url)