Control and Grid Synchronization of Wind Power Systems

Presented By

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Course Outline

- Basic concept of wind power generation
- Power Converter Topologies for wind Generation
- Power electronics Control of wind generation
- Grid synchronization algorithm for wind generation
- Summary and conclusions
Research Motivation

• Due to depletion of fossil fuels and the increasing demand of electrical energy leads to generate electricity from wind and it has an impact with great potential.

• Wind energy is the fastest growing and most promising renewable energy source among all renewable energy sources, due to economically viable and wind energy conversion systems (WECS) are today’s one of the most popular research topic that the researchers are intensively carrying on.

• In Poland, the total installed capacity of wind power generation is 3390 MW in the year 2013. By the end of 2015, the total installed capacity is to be 5000 MW (6% of total installed capacity) according to GWEC, USA.

• In terms of wind power installed capacity, Poland is ranked 8th in the world. Today Poland is a major international player in the global wind energy market.
Global Installed Capacity of Wind Power

**TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2013**

<table>
<thead>
<tr>
<th>Country</th>
<th>MW</th>
<th>% SHARE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PR China</strong></td>
<td>16,100</td>
<td>45.4</td>
</tr>
<tr>
<td>Germany</td>
<td>3,238</td>
<td>9.1</td>
</tr>
<tr>
<td>UK</td>
<td>1,883</td>
<td>5.3</td>
</tr>
<tr>
<td>India</td>
<td>1,729</td>
<td>4.9</td>
</tr>
<tr>
<td>Canada</td>
<td>1,599</td>
<td>4.5</td>
</tr>
<tr>
<td>USA</td>
<td>1,084</td>
<td>3.1</td>
</tr>
<tr>
<td>*Brazil</td>
<td>948</td>
<td>2.7</td>
</tr>
<tr>
<td>Poland</td>
<td>894</td>
<td>2.5</td>
</tr>
<tr>
<td>Sweden</td>
<td>724</td>
<td>2.0</td>
</tr>
<tr>
<td>Romania</td>
<td>695</td>
<td>2.0</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>6,573</td>
<td>18.5</td>
</tr>
<tr>
<td><strong>Total TOP 10</strong></td>
<td>28,894</td>
<td>81</td>
</tr>
<tr>
<td><strong>World Total</strong></td>
<td>35,467</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Typical Wind Turbine Generator

The basic structure of wind turbine system is illustrated in above figure, which includes wind turbine rotor, a gearbox, a generator, a power electronic converter system, and a transformer for grid connection.
• Wind turbine components
  – wind turbine runs at low speed (0.5 Hz)
  – mechanical drive train includes a gear box
    • converts low speed of turbine to high speed of generator
• Mechanical speed regulation:
  – blade pitch angle control
    • each blade rotated about longitudinal axis
    • variable speed
  – stall control
    • no pitch actuators required
    • fixed speed
• Types of generators
  – induction generator
  – synchronous generator
  – doubly fed induction generator
• WTG ratings range from 25 kW to 3 MW
Variable Speed Wind Power Generation

- Variable speed turbines can be made to capture this maximum energy in the wind by operating them at a blade speed that gives the optimum tip speed ratio. This may be done by changing the speed of the turbine in proportion to the change in wind velocity.

- The output mechanical torque and power of the wind turbine, respectively, can be calculated from the equations:

  \[ T_m = \frac{1}{2} \rho \cdot A \cdot R \cdot C_p \cdot V_w^2 / \lambda \]

  \[ P_m = \frac{1}{2} \rho \cdot A \cdot C_p \cdot V_w^3 \]

Here, \( \rho \) is the air density (usually 1.225 kg/m\(^3\) at 15\(^\circ\)C and normal pressure) and A is the swept area by the blades.
As one can see, the maximum power follows a cubic relationship with turbine speed.

The wind turbine is characterized by the plot of the power coefficient $C_p$ as a function of both tip speed ratio, $\lambda$, and the blade pitch angle, $\beta$. Typical $C_p - \lambda$ curves for the pitch angle changing from 0 to 20° are shown in above Fig. There is a value of the tip speed ratio at which the power coefficient is maximum.
Typical Wind Turbine “Power Curve”

- Fig below shows typical output versus wind speed characteristics of wind turbines:

- The cut-in, rated and cut-out speeds shown are typical for utility-scale WTGs.

- Generally, WTGs are designed to work at maximum aerodynamic efficiency between cut-in and rated wind speed.

- For wind speeds higher than rated and lower than cut-out:
  - blade pitching or blade stalling is used to maintain loading within the equipment’s rating.

- WTGs shut down for wind speeds higher than cut-out speed to avoid excessive mechanical stress.
Generator Configuration for Variable Speed Wind Energy Conversion System

Presently four major types of WTG Technologies used:
1. Squirrel Cage Induction Generators driven by fixed-speed, stall-regulated wind turbines
2. Induction Generators with variable external rotor resistance driven by a variable-speed, pitch regulated wind turbines
3. Doubly-Fed Induction Generators driven by variable-speed, pitch regulated wind turbines
4. Synchronous or Induction Generators with full converter interface (back-to-back frequency converter), driven by variable-speed, pitch regulated wind turbines
(a) Wind turbine system with SCIG

(b) Wind turbine system based on DFIG

(c) Wind turbine system based on PMSG
Doubly-Fed Induction Generator (DFIG) with Back-to-Back Converter

• At the synchronous speed, the inverter connected with the rotor is working in chopping mode so that the generator can be excited by injecting DC currents into the rotor.
• The generator is able to operate below, above and at synchronous speed successively. The speed range is restricted only by the rotor voltage ratings of the DOIG.
• The two IGBT converters operate as inverters to adjust both output sinusoidal currents, so the generator torque and rotor excitation can be controlled independently. The DC link capacitor smoothen the DC voltage.
• The system power factor can be controlled by the network side converter or machine side converter, depending on operation levels and conditions.
• Efficiency Improvement to 2% to 3%
• Converter power rating is only 25% of total system power.
• Therefore, the DFIG is the only the power generating scheme in which the generator gives more than its rated power without being overheated and the power generation can be realized in a wide range of wind speeds
Part-2: CONVERTER TOPOLOGIES FOR DFIG SYSTEM

**Note:** The DFIG with variable speed operation is an excellent choice for high power applications in the MW range. *Enercon* fabricated a wind turbine of 4.5 MW with rotor diameter of 112.8 meters using DFIG.

The static Kramer drive consists of a diode rectifier on the rotor side and a line commutated inverter connected to the grid side as illustrated in above Figure.

This converter is able to provide the active power from both stator and rotor sides respectively, under super-synchronous operation only.

The replacement of diode rectifier by SCR converter in the rotor side allows the generator to receive reactive power from via rotor-side converter system, and the active power flow is bi-directional.
The back-to-back rectifier-inverter pair is a bidirectional power converter consisting of two conventional pulse-width modulated (PWM) voltage-source converters (VSC), as shown above.

One of the converters operates in the rectifying mode, while the other converter operates in the inverting mode. These two converters are connected together via a dc-link consisting of a capacitor. The dc-link voltage will be maintained at a level higher than the amplitude of the grid line-to-line voltage, to achieve full control of the current injected into the grid.
Resonant DC-link Converter for DFIG System

Above Fig. shows the resonant DC link uses one resonant circuit to provide soft switching for the entire converter. The DC link is forced to oscillate, so the resonance circuit is located on the DC link side and not on the load side, since only one resonant circuit is required instead of one for each phase.

The idea behind the use of resonant converter is that ideally the converter should only change state at zero link voltage. The resonant circuit is formed by $L_{res}$ and $C_{res}$, where the resonant capacitor is usually having the value less than the DC link capacitor $C_{dc}$.

The resonant link voltage swings between zero and twice the DC link voltage, which means that the voltage rating of the switches has to be higher.
Matrix converter is a one-stage AC/AC converter capable of converting the variable AC from the generator into constant AC to the grid that is composed of an array of nine bidirectional semiconductor switches, connecting each phase of the input to each phase of the output.

Two distinct advantages arise from this topology, the converter requires no bulky energy storage or dc-link and control is performed on just one converter.

The basic aim of using matrix converter is that a desired output frequency, output voltage and input displacement angle can be obtained by properly operating the switches that connect the output terminals of the converter to its input terminals.
## Converter Topology Comparison for Wind Energy System

<table>
<thead>
<tr>
<th>Generator (power range)</th>
<th>Converter options</th>
<th>Device count (semiconductor cost)</th>
<th>Control schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode bridge/SCR inverter</td>
<td>DC-link cap. 6 controllable switches (low)</td>
<td>Sliding mode control</td>
<td></td>
</tr>
<tr>
<td>SCR rectifier/SCR inverter</td>
<td>DC-link cap. 12 controllable switches (Moderate)</td>
<td>Dual thyristor firing angle control</td>
<td></td>
</tr>
<tr>
<td>Back-to-back hard-switching inverters</td>
<td>DC-Link cap. 12 controllable switches (moderate)</td>
<td>Vector control of rotor and supply side space vector modulation or PWM MPPT, space vector control</td>
<td></td>
</tr>
<tr>
<td>Matrix converter</td>
<td>18 controllable switches (high)</td>
<td>Vector control of rotor and supply side double space vector PWM switching</td>
<td></td>
</tr>
</tbody>
</table>
Part-3 Power Electronics Control of Wind Power Generation System

Power Electronics Control Concepts

• Variable speed wind turbines are designed to operate at maximum aerodynamic efficiency over a wide range of wind speed over fixed speed wind turbines and they are usually equipped with an induction or synchronous generator connected to the grid through a power electronic converter.

• The prime role of power electronic converter is to interface the wind turbine generator with the grid to meet the following objectives.
  1) To reduce the mechanical stress on the mechanical components during wind speed variation
  2) To capture the maximum wind energy
  3) To reduce the acoustic noise etc.
  4) Moreover, power electronic converter can provide extra features to meet the new “Grid Code Compliances (GCC)” issued by the utility authorities.

*Power electronic control concepts in the wind turbine systems highly involves in higher wind energy capture through maximum power point tracking (MPPT) and achieving grid code requirements.*
Grid-Side Converter Modeling and Its Control

\[ V_{dc} \]

3-Φ Grid Side VSI

DC Link

Modulator

Current Controller

\[ S_i \]

\[ V_{c,i} \]

\[ \ell_{g,i} \]

\[ i_{g,i} \]

\[ i_{g,i,\text{ref}} \]

\[ L_{g,i} \]

\[ V_{g,i} \]
Control Structure of Current Controlled Grid-Side Converter

The control strategy normally employs two cascaded loops;

• Internal current loop in order to regulate the grid current and is responsible for power quality issues and current protection. Thus, it inherits important attributes of harmonic compensation and dynamics.
• External voltage loop to control dc-link voltage and to balance the power flow in the system. The design aims for system stability with slow dynamics.

The other control strategies possible are:

• A dc link voltage loop cascaded with an inner power loop instead of a current loop, thereby controlling the injected current into the utility grid indirectly.
• An output power loop cascaded with an inner current loop.
Modeling of Grid-Side Converter

The three phase supply voltage is given by

\[ V_a = V_m \cos \omega t \]
\[ V_b = V_m \cos(\omega t - 2\pi/3) \]
\[ V_c = V_m \cos(\omega t + 2\pi/3) \]
\[
\begin{bmatrix}
\frac{di_a}{dt} \\
\frac{di_b}{dt} \\
\frac{di_c}{dt}
\end{bmatrix} = \frac{-R}{L} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} (u_a - V_a) \\ (u_b - V_b) \\ (u_c - V_c) \end{bmatrix}
\]

Coordinate transformations given below from three phase stationary (ABC) to two phase stationary (αβ) (equal turn transformation):

\[
\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & 1 & -1 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \sqrt{3} \cos \omega t \\ \frac{3}{2} \sin \omega t \end{bmatrix}
\]
From equation (3.2) and (3.3), the following equation is obtained:

\[
\begin{bmatrix}
V_\alpha \\
V_\beta
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & -1 \\
2 & 2 & 2 \\
\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
u_a - L \frac{di_a}{dt} \\
u_b - L \frac{di_b}{dt} \\
u_c - L \frac{di_c}{dt}
\end{bmatrix} =
\begin{bmatrix}
u_\alpha - L \frac{di_\alpha}{dt} \\
u_\beta - L \frac{di_\beta}{dt}
\end{bmatrix}
\]

Transformation from the stationary α–β to the synchronous d–q frame, which is rotating with the angular frequency ω, can be obtained as follows:

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} =
\begin{bmatrix}
cos \omega t & sin \omega t \\
-sin \omega t & cos \omega t
\end{bmatrix}
\begin{bmatrix}
u_\alpha \\
u_\beta
\end{bmatrix} -
\begin{bmatrix}
cos \omega t & sin \omega t \\
-sin \omega t & cos \omega t
\end{bmatrix}
\begin{bmatrix}
L \frac{di_\alpha}{dt} \\
L \frac{di_\beta}{dt}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
u_d \\
u_q
\end{bmatrix} - \begin{bmatrix}
cos \omega t & sin \omega t \\
-sin \omega t & cos \omega t
\end{bmatrix} \cdot L \frac{d}{dt} \begin{bmatrix}
cos \omega t & sin \omega t \\
-sin \omega t & cos \omega t
\end{bmatrix}^{-1} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
\]

Contd.,
Hence

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} =
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} - L \frac{d}{dt} \begin{bmatrix}i_d \\
i_q
\end{bmatrix} + \omega L \begin{bmatrix}i_q \\
-i_d
\end{bmatrix}
\]

The output voltages of the grid-connected inverter in the synchronous d – q frame are given by

\[
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} = L \frac{d}{dt} \begin{bmatrix}i_d \\
i_q
\end{bmatrix} + \omega L \begin{bmatrix}-i_q \\
i_d
\end{bmatrix} + \begin{bmatrix}V_d \\
V_q
\end{bmatrix}
\]
Three phase reference currents have been made from $i_d$ ref and $i_q$ ref by using the synchronous reference frame to a-b-c transformation that is given below

$$
\begin{bmatrix}
i_{Ld} \\
i_{Lq} \\
i_{L0}
\end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix}
\cos(\omega t) & \cos(\omega t - (2\pi/3)) & \cos(\omega t + (2\pi/3)) \\
\sin(\omega t) & -\sin(\omega t - (2\pi/3)) & -\sin(\omega t + (2\pi/3)) \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} X 
\begin{bmatrix}
i_{La} \\
i_{Lb} \\
i_{Lc}
\end{bmatrix}
$$

$$
\begin{bmatrix}
i_{a\text{ref}} \\
i_{b\text{ref}} \\
i_{c\text{ref}}
\end{bmatrix} = \begin{bmatrix}
\sin(\omega t) & \cos(\omega t) & 1 \\
\sin(\omega t - (2\pi/3)) & \cos(\omega t - (2\pi/3)) & 1 \\
\sin(\omega t + (2\pi/3)) & \cos(\omega t + (2\pi/3)) & 1
\end{bmatrix} X 
\begin{bmatrix}
i_{La} \\
i_{Lb} \\
i_{Lc}
\end{bmatrix}
$$
Grid Flux oriented Control of Grid-connected Inverter

- In the fig. shown the grid flux vector is aligned with the d-axis and grid voltage vector is aligned with the q-axis.

- Vector control regulates the length and position of the grid current vector in the grid flux oriented reference frame.

- In this reference frame the real part of current corresponding to reactive power and imaginary part of current corresponds to active power.

- The active current component is generated by an outer direct voltage control loop and the reactive current reference can be set to zero for a unity power factor.
The grid side converter consists of two control loops.

- Outer DC control voltage loop.
- Inner current control loop.

**DC Voltage Controller**
- It is used to produce the reference current value for the current controller.
- Its aim is to keep the voltage constant on the DC side in normal condition or grid faults or changes in input power.

The instantaneous power flowing into the grid can be written as:

\[ S_g = P_g + jQ_g = \frac{3}{2} e_{gq} i_{gq}^* = \frac{3}{2} (e_{gq} i_{gq} + j e_{gq} i_{gd}) \]

\[ S_g = \frac{3}{2} (|e_g| i_{gq} + j |e_g| i_{gd}) \]

From the eq. of instantaneous power, the active power is the real part of above eqn., is written as:

\[ P_g = \frac{3}{2} (|e_g| i_{gq}) \]
When neglecting the capacitor leakage, the direct voltage link power is given by

\[ P_{dc} = U_{dc} i_{dc} = U_{dc} C \frac{dU_{dc}}{dt} \]

Assuming the converter losses can be neglected, the power balance in the direct voltage link system is given by

\[ U_{dc} C \frac{dU_{dc}}{dt} = P_s - P_g = P_s - \frac{3}{2} |e_g| i_{gq} \]
Where \( P_s \) is the supply power independent of DC link voltage. The transfer function between direct voltage and grid current \( i_{gq} \) can be obtained as

\[
U_{dc} = -\frac{3|e_g|}{2pCU_{dc}} i_{gq}
\]

Substituting the direct voltage with its reference value

\[
U_{dc} = -\frac{3|e_g|}{2pCU_{dc}}^* i_{gq}
\]

\[
U_{dc} = -G_i^* i_{gq}
\]

During normal operating condition, grid voltage amplitude is assumed constant.

Applying internal model control gives the direct voltage link controller as:

\[
F = \frac{\alpha}{p} G^{-1} = -\alpha \frac{2CU_{dc}^*}{3e_g} = K_p
\]

The controllers integration time is:

\[
T_i = \frac{10}{\omega_c} = \frac{10}{\alpha}
\]
Where \( \omega_c \) is the cross-over frequency and \( \alpha \) is the desired band width.

The active reference current of grid connected inverter is given by:

\[
i_{gq}^* = K_p \left(1 + \frac{1}{T_{ip}}\right) \left(U_{dc}^* - U_{dc}\right)
\]

**Figure**: Block diagram of the closed-loop direct voltage control.

**Open loop Reactive Power Component**
Reactive power exchange with the grid is controlled by the reactive current component. Taking the imaginary part of eqn.(36) gives the reactive reference current as

\[
i_{gd}^* = \frac{2}{3e_{gq}} Q^*
\]
Control strategy of grid-connected VSI system
Results & Discussions

The obtained results in the Simulink are verified experimentally in the laboratory by using TMS320F2812 DSP platform.

The simulation parameters are as follows:

DC link reference voltage \( (U_{dc}^*) = 600\text{V} \),
Grid active power \( (P) = 3.5 \text{ kW} \)
Reference Reactive Power \( (Q^*) = 0 \text{ Var} \),
Hysteresis Band Width \( (h) = 0.5 \),
Proportional gain \( (K_p) = 0.05 \), Integral gain \( (K_i) = 20 \).
Experimental Set-up
Overall block diagram of Implemented Converter System
Simulation Results

Figure: Simulation results of DM(a) Grid current (b) Reference current (c) grid Current Vs Current error (d) DC link voltage (e) Inverter o/p voltage Vs Grid voltage (f) Active and Reactive Power
Figure: Simulation results of (a) Power Factor (b) %THD.
Experimental Results

Figure: Experimental Results  
(a) Grid voltage  
(b) grid Current  
(c) Current Vs Current error  
(d) Inverter o/p voltage Vs Grid voltage  
(d) Voltage Vs current  
(e) DC link voltage

02/April/2014  
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Figure: Experimental Results (a) Active and Reactive Power (b) %THD
Conclusions & Summary

• In this work, a control scheme for grid-side converter (GSC) for wind turbine driven DFIG has been developed.

• Further, grid-side converter (GSC) is controlled by a grid-flux orientated vector control scheme that uses a SVPWM with PI-controller.

• From the study, the experiment results show that the control strategy has a good sinusoidal current, a small harmonic component, a fast dynamic response and a perfect system performance.
Part-4 Grid Synchronization of Wind Generation Systems

Wind Energy Integration with Utility Grid

Possible Problems:
- Intermittency
- Generation Unit Not aligned with Load Pattern
- Forecast Uncertainty
- Operational Performance Issues (Low System Inertia)
- Voltage Congestion During Islanding

Solution: *(To meet Grid Code Requirements)*
- Controllable active and reactive power in the grid
- Influence on Grid Stability
- Improved Power Quality
- Quick Response under transients in the Power System

Interconnection of distributed power generating system to utility grid is essential in countries like Denmark and India where wind farms are mostly used to generate some part of electricity.

In India, the wind energy is concentrated in rural areas with a very high penetration. In these cases, the wind power has an increasing influence on the power quality on the weak grids.

The critical power quality issues related to integration of wind farms in weak grids in India are

1. Grid availability and capacity
2. Reactive power
3. Voltage unbalance
4. Voltage ranges
5. Frequency range
6. Harmonics and inter-harmonics
7. Voltage fluctuations
fortunately, these concerns are in part due to older SCR type power inverters that are line commutated and produce high levels of harmonic current. Most new inverter designs are based on IGBTs that use pulse width modulation to generate the injected "sine" wave.

• Rotating generators such as synchronous generators can be another source of harmonics. Depending on the design of the generator windings (pitch of the coils), core non-linearity, grounding and other factors, there can be significant harmonics.

• In extreme cases, equipment at the DG site may need to be de-rated due to added heating caused by harmonics. Any DG installation design should be reviewed to determine whether harmonics will be confined to the DG site or also injected into the utility system.

• Any analysis should consider the impact of DG currents on the background utility voltage distortion levels. The limits for utility system voltage distortion are 5% for Total Harmonic Distortion (THD) and 3% for any individual harmonic.

Requirements of DGs interconnected with utility grid

1) **Voltage Regulation**- A DGs shall not cause voltage at the point of common coupling to go outside of a specified range. For a 120/240V single-phase power system, the maximum voltage is 126/252V and the minimum voltage is 114/226V. For a 600V three-phase power system, the maximum voltage is 630V and the minimum voltage is 570V.

2) **System Frequency**- For interconnected systems operating at 50 Hz AC, frequency deviations shall be limited to a specified range. IEEE-929 recommended that this range be 49.5 - 50.2 Hz for low power systems, which is generally accepted for DGs.

3) **Synchronization**- When synchronizing with an area electric power system, a DGs shall not cause a voltage fluctuation at the PCC more than ± 5% of the prevailing voltage level.

4) **Monitoring Provisions**- A distributed power generator of 250 kW or larger shall have provisions for monitoring connection status, and real and reactive power output at the point of DGs connection.
5) **Isolation Operation** - When required by the area EPS operating practice, a readily accessible, lockable, visible-break isolation device shall be located between the DG unit and the area EPS.

6) **Grounding** - The grounding scheme and the grounding fault protection of DGs should be coordinated with the EPS operators. Electrical Codes provide general guidelines for grounding.

7) **Voltage Disturbances** - An interconnection system shall detect the **rms** or **fundamental frequency** value of the voltage. At abnormal voltages, a DG shall cease to energize the EPS within a specified clearing time. Response to abnormal voltage is depicted in the Table below.

<table>
<thead>
<tr>
<th>Voltage at PCC</th>
<th>Maximum Trip Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>V&lt;60 (V&lt;50%)</td>
<td>6 cycles</td>
</tr>
<tr>
<td>60≤V&lt;106 (50%≤V&lt;88%)</td>
<td>120 cycles</td>
</tr>
<tr>
<td>106≤V&lt;132 (88%≤V&lt;110%)</td>
<td>Normal operation</td>
</tr>
<tr>
<td>132≤V&lt;165 (110%≤V&lt;137%)</td>
<td>120 cycles</td>
</tr>
<tr>
<td>165≤V (137%≤V)</td>
<td>2 cycles</td>
</tr>
</tbody>
</table>
8) **Frequency Disturbances** - A DGs shall follow the interconnected area EPS frequency in its normal range, and shall cease to energize the EPS within a specified time (e.g. 5 or 6 cycles) if the frequency is outside this normal range.

9) **Loss of Synchronism** - A DGs of 250 kW or larger shall be equipped with loss of synchronism protection functions to disconnect the DPG from the area Electric Power System EPS without intentional time delay.

10) **Reconnection** - After an out-of-bounds disturbance, a DG shall cease to energize the area (EPS), and shall remain disconnected until the area EPS voltage and frequency have returned to and maintained normal ranges for 5 minutes.

11) **Anti-Islanding** - Island is a condition in which a portion of an area EPS is energized solely by its distributed generators and loads, while electrically isolated from the remainder of the area EPS. A DG shall detect the island condition and cease to energize the area EPS within 2 seconds of the formation of an island.
12) **DC Current Injection** - A DG system and its interconnection system shall not inject dc current greater than 0.5% of its rated output current into the area EPS at the point of common coupling.

13) **Flicker** - Flicker is considered objectionable when it causes a fluctuation of the light level of incandescent or fluorescent lamps sufficient to be sensed by human eyes. A DGs shall not create objectionable flicker for other customers on the Area EPS.

**Source:** Liuchen et all, “Review of Interconnection Standards for Distributed Power Generation, IEEE LESAC 2002,
Grid Connection Requirements

The following conditions should be met, with voltages in RMS and measured at the point of utility connection.

<table>
<thead>
<tr>
<th>VOLTAGE (at point of utility connection)</th>
<th>Maximum Trip Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>V &lt; 0.5 x V$_{\text{nominal}}$</td>
<td>0.1 sec.</td>
</tr>
<tr>
<td>50% ≤ V &lt; 85%</td>
<td>2.0 sec.</td>
</tr>
<tr>
<td>85% ≤ V ≤ 110%</td>
<td>Continuous Operation</td>
</tr>
<tr>
<td>110% &lt; V &lt; 135%</td>
<td>2.0 sec.</td>
</tr>
<tr>
<td>135% ≤ V</td>
<td>0.05 sec.</td>
</tr>
</tbody>
</table>

- When the utility frequency is outside the range of +/- 1Hz the inverter should cease to energize the utility line within 0.2 seconds.
- DG System shall have an average lagging power factor greater than 0.9 when the output is greater than 50% rated.

Thus the grid voltage and frequency should be estimated and monitored fast and accurate enough in order to cope with the standard.
Objectives of the study

- A converter-interfaced wind power system requires a fast and exact detection of phase and fundamental frequency of grid current in order to implement the control algorithm of power converters by generating reference currents signals.

- Moreover, a desired synchronization algorithm must detect the phase angle of the fundamental component of grid currents as fast as possible while adequately eliminating higher order harmonic components.

- This study presents a grid synchronization algorithm for converter-interfaced DG systems based on recursive Discrete Fourier Transform (DFT) filtering.

- The overall performance of studied recursive DFT filtering is analysed and the obtained computer simulation results are compared with Synchronous Reference frame (SRF) PLL method to confirm the feasibility of the study.
Phase Locked Loop (PLL) tuning

Reference: \[ v_{in} = A \sin(\omega_{in} t + \phi_{in}) \]

VCO output: \[ v_{VCO} = \cos(\omega_{c} t + \phi_{out}) \]

VCO angle: \[ \phi = \omega_{c} t + k_{o} \int s_{e} dt \rightarrow \phi_{out} = k_{o} \int s_{e} dt \]

PD/Mixer output: \[ v_{d} = A k_{d} \sin(\omega_{in} t + \phi_{in}) \cos(\omega_{c} t + \phi_{out}) = \frac{A k_{d}}{2} \left[ \sin((\omega_{in} + \omega_{c}) t + \phi_{in} + \phi_{out}) + \sin((\omega_{in} - \omega_{c}) t + \phi_{in} - \phi_{out}) \right] \]

if \[ \omega_{c} \equiv \omega_{in} \]
\[ v_{d} \approx \frac{A k_{d}}{2} \left[ \sin(2\omega_{in} t + \phi_{in} + \phi_{out}) + \sin(\phi_{in} - \phi_{out}) \right] \]

if \[ \phi_{in} \approx \phi_{in} \]
\[ \sin(\phi_{in} - \phi_{out}) \approx (\phi_{in} - \phi_{out}) \]
\[ v_{d} \approx \frac{A k_{d}}{2} \left[ \sin(2(\omega_{in} t + \phi_{in})) + (\phi_{in} - \phi_{out}) \right] \]

The average value is
\[ \overline{v}_{d} \approx \frac{A k_{d}}{2} (\phi_{in} - \phi_{out}) \]
Three-phase Synchronous Reference Frame (SRF) PLL

\[ v_{sd} \equiv |\hat{v}_s| \]

\[ \hat{\omega} = \frac{1}{s} \]

\[ \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} v_s \sin(\omega t - \hat{\theta}) \\ v_s \cos(\omega t - \hat{\theta}) \end{bmatrix} \]

\[ v_s = v_s^+ \left[ \begin{array}{cc} \cos(\omega t - \hat{\theta}) & -\sin(\omega t - \hat{\theta}) \\ \sin(\omega t - \hat{\theta}) & \cos(\omega t + \phi^- - \hat{\theta}) \end{array} \right] + v_s^- \left[ \begin{array}{cc} \cos(-\omega t + \phi^- - \hat{\theta}) & -\sin(-\omega t + \phi^- - \hat{\theta}) \\ \sin(-\omega t + \phi^- - \hat{\theta}) & \cos(-\omega t + \phi^- - \hat{\theta}) \end{array} \right] \]

Balanced voltage

Unbalanced voltage
The SRF is not able to track instantaneous evolution of the voltage vector when the PLL bandwidth is low.

Near of synchronization: \( \theta' \approx \omega t \)

\[
\sin(\omega t - \theta') \approx \omega t - \theta' \\
\cos(\omega t - \theta') \approx 1 \\
-\omega t - \theta' \approx -2\omega t
\]

\[
v_{S(dq)} \approx V_s^{+1} \left[ \frac{1}{\omega t - \theta'} \right] + V_s^{-1} \left[ \frac{\cos(-2\omega t)}{\sin(-2\omega t)} \right]
\]

\[
v_{sq} \approx V_s^{+1} \left[ \omega t - \frac{V_s^{-1}}{V_s^{+1}} \sin(2\omega t) - \theta' \right] = V_s^{+1} [\psi - \theta']
\]

\[
\psi = \omega t - \frac{V_s^{-1}}{V_s^{+1}} \sin(2\omega t)
\]

\[
P(s) = \frac{\dot{\theta}}{\psi}(s) = \frac{2\xi\omega_s + \omega_c^2}{s^2 + 2\xi\omega_s s + \omega_c^2}
\]

\[
\xi = \frac{k_p}{2} \sqrt{\frac{V_s^{+1}}{k_i}} \\
\omega_c = \sqrt{\frac{V_s^{+1}}{k_i}}
\]
Detailed Analysis SRF PLL

Schematic diagram of SRF PLL system

\[ V_a = V_m \sin \omega t \]
\[ V_\beta = V_m \cos \omega t \]
\[ V_d = V_d^* \]
\[ V_q \]
\[ \Theta^* \]
\[ \omega_{ff} \]
\[ \omega^* \]
To obtain the phase information, the three phase (\(V_a, V_b\) and \(V_c\)) grid voltages are transformed into two phases (\(V_\alpha\) and \(V_\beta\)) in stationary reference frame (\(\alpha\beta\)) by using Clark’s transformation. \(V_{\alpha\beta} = \mathbf{T}_{\alpha\beta} V_{abc}\)

Two phases (\(V_\alpha\) and \(V_\beta\)) are further transformed into direct and quadrature (\(V_d\) and \(V_q\)) axis components in synchronously rotating reference frame (\(dq\)) by using Park transformation. \(V_{qd} = \mathbf{T}_{qd} V_{\alpha\beta}\)

\[
\begin{bmatrix}
V_q \\
V_d
\end{bmatrix} = \begin{bmatrix}
V_m \cos(\theta - \theta^*) \\
-V_m \sin(\theta - \theta^*)
\end{bmatrix}
\]

(1)
Phasor representation of SRF

Then the phase angle $\theta$ is tracked by synchronously rotating voltage space vector along $q$ or $d$ axis by using PI controller.

The voltage phase vector $V$ synchronised with $q$-axis, and hence the transformation become

$$
T_{qd} = \begin{bmatrix}
\sin \theta^* & \cos \theta^* \\
-\cos \theta^* & \sin \theta^*
\end{bmatrix}
$$

(1)

where $\theta^*$ is the estimated phase angle of the PLL system.
Carry out the transformation by using equation $V_{qd} = T_{qd} V_{\alpha \beta}$ yields (2),

$$
\begin{bmatrix}
V_q \\
V_d
\end{bmatrix} = \begin{bmatrix}
\sin \theta^* & \cos \theta^* \\
-\cos \theta^* & \sin \theta^*
\end{bmatrix} \begin{bmatrix}
V_m \sin(\theta) \\
V_m \cos(\theta)
\end{bmatrix}
$$

By applying matrix multiplication and trigonometric formulas we get (3),

$$
\begin{bmatrix}
V_q \\
V_d
\end{bmatrix} = \begin{bmatrix}
V_m \cos(\theta - \theta^*) \\
-V_m \sin(\theta - \theta^*)
\end{bmatrix}
$$

The phase angle $\psi$ is following estimated phase angle $\psi^*$ which is derived from the estimated frequency $\omega^*$. The estimated frequency is the sum of the PI controller output and feed forward frequency $\omega_{ff}$. The gain of the PI controller is designed such that, $V_d$ follows the reference value $V_{d^*} = 0$ as shown in figure in the next slide.
The phase angle $\theta$ is following estimated phase angle $\theta^*$ which is derived from the estimated frequency $\omega^*$.

The estimated frequency is the sum of the PI controller output and feed forward frequency $\omega_{ff}$.

$V_d$ follows the reference value $V_d^* = 0$. If $V_d = 0$ the space vector voltage is synchronized along the $q$-axis and estimated frequency $\omega^*$ locked on the system frequency $\omega$. So the estimated phase angle $\theta^*$ is equals to the phase angle $\theta$. 
Transfer Function and PI controller Design

Usually, the transfer function for the closed loop structure of PLL composed of proportional and integrating element. So the gain is given by;

\[ G = \left( \frac{1}{1 + sT_s} \right) \left( \frac{1}{s} \right) \]  \hspace{1cm} (4)

Hence, transfer function for PI controller is,

\[ G_{PI} = \left( K_p + \frac{K_i}{s} \right) = \frac{\left( K_p \right) \left( 1 + \frac{K_p}{K_i} \right) s}{\left( \frac{K_p}{K_i} \right) s} \]  \hspace{1cm} (5)

\[ G_{PI} = \frac{K_p \left( 1 + \tau \ast s \right)}{\tau \ast s} \]  \hspace{1cm} (6)

where \( T_s \) is sampling period and \( \tau \) is constant.
Usually, the transfer function for the closed loop structure of PLL composed of proportional and integrating element. So the gain is given by;

The open loop transfer function for SRF PLL

\[ G_{ol} = G_{plant} \ast G_{PI} \quad (7) \]

\[ G_{ol} = \left( K_p \frac{1+s\tau}{s\tau} \right) \left( \frac{1}{1+sT_s} \right) \left( \frac{V_m}{s} \right) \quad (8) \]

The closed loop transfer function for the system is

\[ G_{cl} = \frac{G_{ol}}{1+G_{ol}} \quad (9) \]

The relationship between s domain and z-domain is

\[ s = \frac{z-1}{T_s} \quad (10) \]

Substitute equation (10) in equation (6), we get

\[ G_{PI} = K_p \frac{z-1+\tau}{z-1} \quad (11) \]
The SRF PLL system is second order system, the gains of PI controller was estimated by using symmetrical optimum method (SO). The idea behind the SO method is to optimize the phase margin to have its maximum value at a given cross over frequency $\omega_c$.

The transfer function given as

$$G = \frac{\omega_o^2 (ks + \omega_o)}{s^2(s + k\omega_o)} \quad (12)$$

Rewrite the open loop transfer function of the SRF PLL in equation

$$G_{ol} = kV_m(aT_s) \frac{\left(\frac{as + a}{\tau}\right)}{s^2\left(s + \frac{1}{T_s}\right)} \quad (13)$$

Comparing equation (12) and (13) gives the results of PI controller as follows;

$$\omega_c = \frac{1}{aT_s}$$
$$\tau = a^2T_s \quad (14)$$

For a given sampling period $T_s$ the cross over frequency can be chosen by adjusting the normalization factor $a$. 
Bode plot for the open-loop system

The bode plot shows that both the phase and magnitude curve is symmetric around the crossover frequency ($\omega_c = 2\pi \times 50$). The phase margin is 84.4 degrees at $\omega_c$. 
For a second order system, to measure between crossover frequency $\omega_c$ and the bandwidth $\omega_B$ for the closed loop system is approximately constant when designing the gains by considering higher phase margin which gives less oscillatory response, lower value of $\tau$ decreases the settling time and value of gain effects both phase margin and bandwidth.

And therefore good value for the crossover frequency $\omega_c$ would be around the grid frequency of 50Hz that gives maximum phase margin at 50Hz. The closed loop system will also have the characteristics of a low pass filter with bandwidth $\omega_B = \omega_c / 0.7 = 71.9$ Hz as shown in above figure.
Response of SRF PLL when Harmonic Injection

The three phase input signal contains fundamental frequency of 50 Hz (1 p.u), with 33% of 3rd (0.33 p.u), 25% of 5th (0.25 p.u), 17% of 7th (0.17 p.u), 13% of 9th (0.13 p.u) and 8% of 11th (0.08 p.u) harmonics.
Hence, a **Good Synchronization** technique based on PLL should have the following features:

i) Zero steady-state error for phase angle and for frequency variations

ii) Efficiently track the phase and frequency variations of the utility grid signals,

iii) Reject 3rd order harmonics, disturbances that exist naturally in the grid signal

iv) Have good dynamic performance under grid voltage variation, harmonics, and

v) Should be realizable in practice
Phase detection by Recursive DFT Filtering

The proposed DFT filtering consists of three-phase to two-phase transformation, recursive DFT, Moving average filter, PI controller and Numerically Controlled Oscillator (NCO).
Recursive DFT Algorithm

The DFT produce the k\textsuperscript{th} harmonics of \( x(n) \) at unit time delay and it can be written as,

\[
X_k(n-1) = \sum_{n=-N}^{n-1} x(n)e^{-j2\pi(n-1)k/N} \quad (15)
\]

A new time sample of \( x(n) \) is taken and the DFT at the one time step later \( n \) becomes

\[
X_k(n) = \sum_{n=-N+1}^{n} x(n)e^{-j2\pi(n-1)k/N} \quad (16)
\]

Subtracting (15) from (6), we get

\[
X_k(n) = X_k(n-1) + [x(n) - x(n-N)]e^{-j2\pi(n-1)k/N} \quad (17)
\]

Take Z transform for equation (17), we get

\[
H(Z) = \frac{X_k(n)}{X(n)} = \left[1 - Z^{-N}\right]e^{-j2\pi(n-1)k/N} \quad (18)
\]
The real part of recursive DFT is

\[
\text{Re}[X_k(n)] = \left[1 - Z^{-N}\right] x(n) \frac{\cos(2\pi(n-1)k / N)}{1 - Z^{-1}}
\]  

(19)

The imaginary part of recursive DFT is

\[
\text{Im}[X_k(n)] = \left[1 - Z^{-N}\right] x(n) \frac{(-\sin(2\pi(n-1)k / N))}{1 - Z^{-1}}
\]  

(20)

Based on equations (19) and (20) the DFT structure is shown below
The characteristics equation of moving average filter is expressed as

\[ H_{PI}(Z) = K_P + \frac{K_P T_{enao}}{T_i(1-Z^{-1})} \]  

(21)

- From that, in the Z-plane, the moving average filter has \( N \) zeros equally spaced on the unit circle and it has only one pole at \( Z=1 \) cancels zeros at that location.
- This moving average filter is computationally efficient, performing only one addition, one subtraction and multiplication by a constant per output sample, regardless the value of \( N \). The filter is very sharply tuned and passes only the average value and rejects the harmonics.

**PI Controller**

In order to provide the steady dc input \( \alpha \) to the NCO, even when the phase error tends to zero at steady state, a PI controller is incorporated into the phase detection circuit. Thus the transfer function of the controller in the frequency domain is

\[ H_{PI}(Z) = K_P + \frac{K_P T_{enao}}{T_i(1-Z^{-1})} \]  

(22)

where \( K_P \) is the proportional gain, \( T_i \) integral time constant and \( T_{enao} \) is the enabling time, for the PI block.

- The enabling frequency \( f_{enao} = (1/T_{enao}) \) was fixed at 25.6 kHz. The output of the PI controller is limited to ±1. And the saturation limits are allowed to prevent overflow of the integrator registers, which can incidentally limit the control input \( \alpha \) applied to the NCO.
Numerically Controlled Oscillator (NCO)

The control input to the NCO is $\alpha$, where $\alpha = \cos \psi$ and $-1 < \alpha < 1$; $\psi = 2\pi f_s / f_{enao}$, $f_s$ is output pulse frequency of the NCO and $f_{enao}$ is the fixed enabling frequency at 25.6 kHz. For the condition, $\psi = \pi/2$, $\alpha=0$.

The enabling frequency become

$$f_{enao} = 4f_s$$

The difference equation obeyed by the NCO is

$$
\begin{bmatrix}
    x_1(k+1) \\
    x_2(k+1)
\end{bmatrix}
= \begin{bmatrix}
    \alpha & \alpha - 1 \\
    \alpha + 1 & \alpha
\end{bmatrix}
\begin{bmatrix}
    x_1(k) \\
    x_2(k)
\end{bmatrix}
$$

$x_1(0) = x_2(0) = 0$;

The network diagram of NCO is shown in Figure above. For a 50-Hz input signal and a window width $N=128$, the frequency of the sampling pulses produced by the NCO is 6.4 kHz, when it is enabled by a 25.6 kHz clock.
The inverse DFT of $X_k(n)$ is defined as

$$x_k(n) = \Gamma(k) X_k(n) e^{j2\pi(n-1)k/N}$$

$$\Gamma(k) = \begin{cases} N^{-1} & : k = 0, N/2 \\ 2N^{-1} & : otherwise \end{cases} \quad (23)$$

By taking $Z$-transform for equation (11) and (15), the final simplified form of $Z$-transform of the DFT become when $k=1$ becomes,

$$\frac{x_1(Z)}{X_1(Z)} = \frac{1}{N} \left[ \frac{1-Z^{-N}}{1-e^{j2\pi k/N}Z^{-1}} + \frac{1-Z^{-N}}{1-e^{j2\pi k/N}Z^{-1}} \right] \quad (24)$$

By using equation (24) the frequency response can be determined by using bode plot and pole zero plot methods.
The corresponding frequency response of the DFT filter is with fundamental frequency of 50Hz and sampling frequency of 6400. For low frequencies the magnitude envelope initially rolls off at 30 dB/decade but tends asymptotically to 20 dB/decade such that at 1 Hz the magnitude response is -53.5 dB.

This characteristic shows that filter will attenuate the effect of sub harmonics in the line voltage. For frequency higher than the fundamental frequency the harmonic rejection is clear and the magnitude envelope rolls-off at 20dB/decade up to the sampling frequency.

Therefore the DFT filter shows the band-pass filter(BPF) characteristics.

BPF can reject all the even and odd harmonics including the DC offset and does not introduce any lag/lead phase angle at the fundamental frequency. Therefore, during the time-varying fundamental frequency cases, the DC offset and harmonics of the input grid voltage waveform can be completely eliminated.

The extraction of a single frequency component produces two poles that cancel mutually with zeros and $N-2$ zeros equidistantly spaced on the unit circle.
Results & Discussions

In order to analyse the proposed study simulations tests has been carried out in the MATLAB-Simulink environment and the following parameters are considered for the study.

- Peak value of Input voltage $V_m = 1$ (p.u),
- Fundamental supply frequency $f = 50$Hz,
- Number of sample $N = 128$,
- Enabling frequency $f_{enao} = 25.6$ kHz,
- Proportional constant $K_P = 0.01$,
- Integral constant $K_I = 0.0026$.

The abnormal conditions namely: harmonic injection and frequency variation of grid voltages are examined for accurate phase detection using SRF PLL and recursive DFT algorithm.
The estimated frequency is extracted at accurate sampling rate by using NCO. On the other hand, the proposed recursive DFT filtering is less sensitive to harmonics and grid parameter variations. Moreover, the moving average filter employed to remove the double frequency oscillations (100 Hz) is also useful to nullify the effect of harmonics. As a result, the THD of grid voltage is reduced to 1.68%. as shown in Figure above.
Response of DFT algorithm for Frequency deviation

It is observed that, the proposed DFT filtering can be able to accurately estimate the phase of the fundamental signal during frequency variations. Therefore, the precise detection of phase angle is realised by the proposed DFT filtering method.

Moreover, the estimated frequency is more accurate and there is slight variation in frequency due to variable sample rate of recursive DFT filtering.
Conclusions & Summary

- In the proposed study, it was concluded that the recursive DFT can extract the fundamental frequency of the voltage signal accurately during abnormal operation of the grid.
- Moreover, the transient response of the proposed recursive DFT is very fast as compared to conventional SRF PLL with lower THD of grid voltages/currents.
- The proposed synchronization scheme that in addition to detecting the grid phase angle can detect current harmonics and extract the active/reactive current component for power quality purposes.
- Therefore, the immediate advantages of the proposed PLL are: frequency adaptability, precise harmonic compensation, and structural robustness.
- As a result, the proposed synchronization scheme can further be used for grid measuring, monitoring and processing of the grid signals.
Thank You for your kind Attention