Performance improvement of voltage controlled isolated wind power generation system consisting of linear and non-linear loads

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Abstract. In an isolated mode operation of wind power generating system (WPGS), operating voltage and frequency are affected under sudden change of load because of more transient time, higher total harmonic distortion. To minimize the effects, the WEGS should be operated with suitable controller and the inverter should be operated with required pulse width modulation (PWM) technique. In this paper, the proposed WPGS is simulated using MATLAB/Simulink with adaptive voltage controller (AVC) and load current observer (LCO) and the inverter is operating with Unified voltage Space Vector PWM (USVPWM) technique to improve the transient behaviour of the system. The same proposed system is also simulated with conventional space vector pulse width modulation (SVPWM) techniques. The simulation results will be analyzed in various load conditions. The conventional SVPWM results compared with the USVPWM results like transient time, load voltage and load current total harmonic distortion under balanced three-phase load.

Keywords. Adaptive Voltage Controller, Conventional Space Vector Pulse Width Modulation, Load Current Observer, Unified Voltage Space Vector Pulse Width Modulation, Wind Power Generating System

1. Introduction

Worldwide countries are looking on the way to non-conventional energy based electrical power generation systems to meet increasing electrical load demand. This is because of day by day increasing of population, industry needs and to reduce the increasing of global warming and environmental pollution because of utilization of fossil fuels like coal, natural gas and oil to generate electrical energy [1]. The renewable energy based electrical power generation offers lower per unit cost, stable energy price, increasing the reliability of the energy system when they are integrated with grid, development of local industries and increase job opportunities. In recent years, various types of controllers have been implemented for the effective operation of renewable based power generating units.
Among the renewable sources wind power generation system (WPGS) is one of the best solutions for standalone applications. The repetitive controller with variable sampling / switching period technique (VSPT) has been proposed for the WPGS to get optimal achievement in steady state conditions [2]. The VSPT with simple structure of RC can be used to achieve changing switching frequency ($f_s$) in terms of fundamental frequency with fixed number of samples per operating period. However, repetitive controller response time is more and it has deficiency in systematic method to improve the dynamic response of the system.

A disturbance observer-based fuzzy adaptive voltage controller has designed for the 3-$\phi$ PWM inverter of isolated WECS [3]. This controller has only single control closed path for directly regulating the output voltage and improve the system dynamic response. A disturbance observer is used to forecast disturbances such as sudden load changes, continuous change of system parameters etc. Therefore, it reduces the required number of sensors to improves system performance and reliability. The controller and observer improve the reliability in case of sudden and large disturbances, non-linear loads and system parameter uncertainties, but this controller is mere sensitive.

In the grid connected system, the operating point and conditions continuously changes with respect to load variations. Therefore, grid connected inverters (GCI) are required for stable operation of the system with lower harmonic distortions (good power quality) under any operation conditions. One more important task is that the GCI is effectively operate the system as isolated mode, when the fault is occurred in the grid. The voltage source inverters can effectively operate power system as grid connected mode or grid formation mode with the help of suitable intelligent controllers [4], [5],[6], [10], [11]. In grid connected PV system, the voltage performance is increased by using continuous mixed p-norm algorithm [4]. This algorithm is used for the online change of gains of PI controller. This controller is suitable for PV systems and WPGS. The power quality of the system is improved by various controllers such as a 3-$\phi$ amplitude adaptive notch filter synchronization [5], nonlinear disturbance observer and multi loop PI controller [4] and adaptive frequency estimation observer, nonlinear active disturbance rejection phase-locked loop-based controller [11] and recursive least-squares estimation technique and adaptive minimum variance control to control active and reactive power of the inverter output [7]. A robust adaptive PI voltage controller can be used in Distributed Generation Systems (DGS) for the effective elimination of effect of disturbances and warped model parameters of 3-$\phi$ voltage source inverters [8]-[9].

For the electrification of rural area and islands, isolated mode operation of renewable based electrical energy generation is required with suitable controllers for the effective and stable operation [12]. In this paper, standalone WPGS is simulated with AVC and LCO and the inverter output is controlled by suitable Pulse Width Modulation (PWM) technique. The technical contribution in this paper is the introduction of Unified voltage Space Vector PWM (USVPWM) to the standalone WPGS powering linear and non-linear loads together. For the simulation, combination of Resistive-inductive (R-L) and non-linear load (power electronic converter) is considered which is most commonly seen in the real time applications and the simulation results obtained under balanced load conditions.

2. System description
The configuration of standalone WPGS is shown in the figure 1. In the standalone WPGS, wind generator and AC-DC power converter are replaced with the DC voltage source. The DC bus voltage has ripples because it has higher order and lower order harmonic frequency components. Under balanced load condition, lower order harmonic frequency components effect can be negligible. But in case of unbalanced load, lower and higher order harmonic effects are more. In case of balanced and unbalanced loads, the harmonic effects can be minimized with the pair of capacitors $i.e., C/2$ each. The DC power can be converted into AC power with the inverter. Because of the switching, the inverter output has voltage and current ripples which can be eliminated by using LC filter. The output power is supplied to the 3-$\phi$ Resistive-Inductive (R-L) load and non-linear load. But during the transient period $i.e.,$ sudden change of loads, the output power of the inverter is affected. In this paper, the inverter output is controlled with USVPWM technique to regulate the output voltage and frequency during...
sudden change of loads. The stability and transient response of the system can be improved with adaptive voltage controller (AVC) and load current observer (LCO). If the inverter is operated with Conventional SVPWM technique, it requires large size of processor because more data is stored in look-up table and delay time is more because more calculations required for the sector identification and determination of the magnitude of operating voltage. To overcome the disadvantages, the proposed system is simulated with USVPWM [13-15] and the results are compared with conventional SVPWM [18-29].

3. Controller design

In the figure 1, the controller consists of Load current observer (LCO), adaptive voltage controller and conventional SVPWM or unified SVPWM technique. For the design of LCO, direct and quadrature axis voltages (V_{od} and V_{oq}) and currents (I_{od} and I_{oq}) are considered as inputs to estimate the respective initial estimations of voltages (\hat{V}_{od} and \hat{V}_{oq}) and currents (\hat{I}_{od} and \hat{I}_{oq}). The estimated outputs are given as the inputs to the AVC.

The output equation of LCO is represented as

$$\dot{x} = Ax + MCx - M\dot{C}x + Bu$$  \hspace{1cm} (1)

Where,

$$x = \begin{bmatrix} I_{od} \\ I_{oq} \\ V_{od} \\ V_{oq} \end{bmatrix}, \quad \dot{x} = \begin{bmatrix} \dot{V}_{od} \\ \dot{V}_{oq} \\ \dot{I}_{od} \\ \dot{I}_{oq} \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 1/C_{filter} & 0 \\ 0 & 0 & 0 & 1/C_{filter} \end{bmatrix}, \quad u = \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

The adaptive control theory is used to design AVC [16]. The AVC depends on the existence reference model that brings out the required performance of the voltage control scheme. For the design, inputs are dq-axis currents (I_{sd}, I_{sq}) which are sensed before the filter and voltages (V_{od}, V_{oq}), currents (I_{od}, I_{oq}) are sensed after the filter and dq-axis reference voltages represented as (V_{odref}, V_{oqref}). Before the filter, the inverter performance current equations along dq-axis are

$$I_{sd ref} = I_{sd} - \omega C_{filter} V_{oq}$$  \hspace{1cm} (2)
The dq-axis voltage error after the LC filter equations are
\[ V_{od} = V_{od} - V_{od \, \text{ref}} \]  
\[ V_{eq} = V_{eq} - V_{eq \, \text{ref}} \]  

The dq-axis current error ahead of the filter
\[ I_{sd} = I_{sd} - I_{sd \, \text{ref}} \]  
\[ I_{sq} = I_{sq} - I_{sq \, \text{ref}} \]  

Based on the error, the AVC develop the reference voltage signals which are supplied to PWM technique so as to control the output of the inverter for the effective performance of WPGS. This paper compares two types of PWM techniques. They are conventional SVPWM and unified SVPWM techniques. The conventional Space Vector Pulse Width Modulation (SVPWM) technique is one of the suitable techniques for 3-ϕ voltage source inverter (VSI) to implement in WPGS [16]. In this technique, dq-axis voltages generated by AVC are used to calculate the \( V_{ref} \). The reference voltage vector is resolved in to magnitude and its phase angle which are calculated using the formulae of
\[ |V_{ref}| = \sqrt{V_d^2 + V_q^2} \quad \text{and} \quad \theta = \tan^{-1}\left(\frac{V_q}{V_d}\right) \]  

Based on the angles, the sector is identified and the dwell times are calculated. The dwell times are dependent on the maximum of magnitude of \( V_{ref} \) shown in the figure 2.

Figure 2. Representation of conventional space vector PWM technique in complex plane.
In the conventional SVPWM technique, first identify the location of the reference voltage vector. After that, predetermine the closest active voltage vectors, then calculate the switching or dwell times. It shows that this technique implementation is more difficult and delay time is more. But in Unified SVPWM technique, each leg switching time of the inverter is directly determined as a simple form on the concept of effective voltage. In this controller technique, accurate switching pattern is effectively applied and implementation time is reduced [13].

In the USVPWM technique, the AVC generated dq-axis voltages are converted into 3-ϕ voltages (V_R, V_Y and V_B) using inverse park’s transformation as

\[
\begin{bmatrix}
V_R \\
V_Y \\
V_B
\end{bmatrix} = \begin{bmatrix}
\cos(\theta) & -\sin(\theta) & 1 \\
\cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) & 1 \\
\cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) & 1
\end{bmatrix} \begin{bmatrix}
V_d \\
V_q \\
V_0
\end{bmatrix}
\]

(9)

Using the reference voltages V_R, V_Y and V_B the imaginary timings are calculated as

\[
T^*_R = \frac{V_R}{V_{dc}} \times T_s, T^*_Y = \frac{V_Y}{V_{dc}} \times T_s, T^*_B = \frac{V_B}{V_{dc}} \times T_s
\]

(10)

Now, using three element sorting algorithm, maximum and minimum values from the imaginary timings are determined (T_{max} and T_{min}). Then effective time(T_{eff}), zero time(T_{zero}) and offset time(T_{offset}) are calculated with the following formulae.

\[
T_{eff} = T_{max} - T_{min}
\]

(11)

\[
T_{zero} = T_{s samp} - T_{eff}
\]

(12)

\[
T_{offset} = \left(\frac{T_{zero}}{2}\right) - T_{min}
\]

(13)

Using the offset time (T_{offset}), the switching times are calculated as

\[
T_{GR} = T_R + T_{offset}
\]

(14)

\[
T_{GY} = T_Y + T_{offset}
\]

(15)

\[
T_{GB} = T_B + T_{offset}
\]

(16)

The switching time waveforms are compared with the triangular waveform to generate the gate pulses and they are applied to the inverter to regulate the load voltage and frequency under sudden change of load conditions.

4. Simulation results analysis

In this section, the proposed standalone WPGS which is represented in figure.1 is simulated using MATLAB/Simulink under various conditions with the combination of linear load (R-L Load) and non-linear load. The system simulation results are obtained with USVPWM technique which is used to operate the 3-ϕ inverter of proposed system, under balanced and unbalanced loads. From the simulation results, in each case transient response(T_t), percentage of total harmonic distortion (THD) of per phase load voltage and load current are obtained. In addition to the USVPWM technique, it is also simulated with AVC and LCO. The simulation results are compared with the same system which was simulated with the conventional SVPWM technique[18].

In the simulation, the transient behaviour of the system will be analyzed by connecting a 3-ϕ circuit breaker(CB) which is connected before the load. Under balanced loads, all the contacts of the CB are closed at 0.1 sec. After switching, the AVC, LCO and USVPWM are resulting in minimized transient time, the total harmonic distortion of load voltage and load current are also reduced when compared to the conventional SVPWM technique as discussed below.
Results from the proposed system using USVPWM technique under balanced conditions: (a) LCO currents, (b) AVC voltages, (c) inverter line voltage, (d) load phase voltage, (e) load currents, (f) harmonic spectrum of load voltage and (g) harmonic spectrum of load current.

In this case, the inverter 3-ϕ output voltages are controlled by USVPWM technique and AVC. The LCO inputs are set to zero i.e., the proposed system is operating without load current observer. In other words, the load current sensors are used instead of LCO. The simulation results of WPGS under balanced load are shown in figure 3. The figure 3 has transformed inverter currents measured by LCO ($I_{dq}$), transformed voltages generated by AVC($V_{dq}$), line to line voltage ($V_{RY}$), 3-ϕ load voltages ($V_{RYB}$), 3-ϕ load currents ($I_{RYB}$). The THD of load voltage and load current are shown in subplots (f) and (g) respectively. From the figure 3, it is observed that the transient time ($T_{tr}$) of the system is about 30 msec as shown in subplot (b), THD of per phase load voltage is about 2.69% and THD of load current is around 17.75%.

The simulation work is continued and the inverter is now operated with conventional SVPWM technique along with the AVC and LCO. To compare the simulation results of USVPWM technique with conventional SVPWM technique, the simulation results of the WPGS of balanced load is shown in the figure 4. From the results, it can be observed that after sudden change of load i.e., at 0.1 sec, the AVC injects the voltage to compensate the change of the voltage and reduce the transient time. But it is not able to take the instantaneous action and it is non-linear as shown in the subplots (b). Therefore, its transient time, load voltage and load current THDs are more as compared with the results of the system which are simulated with the USVPWM.
The simulation results of WPGS with USVPWM technique are compared with the Conventional
SVPWM [18]. From the results, it can be observed that the transient time is reduced from 30 ms to 20
ms, load voltage THD is changed from 4.32% to 2.69% and load current THD is changed
from 18.19% to 17.75% respectively.

5. Conclusion
In this paper, the proposed isolated WPGS which is shown in figure 1 is simulated using
MATLAB/Simulink software by considering the combination of the 3-ϕ R-L load and non-linear load.
The system is simulated with AVC, LCO and the inverter is operated with conventional USVPWM
technique and SVPWM technique. The simulation results which are obtained with conventional
SVPWM technique are compared with the USVPWM technique. From the results it can be observed
that when the isolated WPGS is operating with USVPWM technique, the performance of the system
can be improved i.e. as compared with conventional SVPWM technique, the transient behaviour of
the system can be improved. THD of load voltages and load currents can be reduced with USVPWM

![Figure 4. Results from the proposed system using conventional SVPWM technique under balanced
conditions: (a) LCO currents, (b) AVC voltages, (c) inverter line voltage, (d) load phase voltage, (e)
load currents, (f) harmonic spectrum of load voltage and (g) harmonic spectrum of load current](image-url)
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