Shunt Active Power Filter Wind Energy Conversion System

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Abstract— **This paper presents a permanent magnet synchronous generator (PMSG) wind energy conversion system (WECS) with the implementation of a current controlled voltage source inverter (CC-VSI) and shunt active power filter (APF) capabilities. The WECS is not only capable of supplying extracted wind power to the load, but also can be used for harmonic mitigation and regulating the active and reactive power injected into the mains. Consequently, a more favorable power system results from the integration of APF into WECS. The proposed WECS control concept and the CC-VSI/APF are verified using a computer simulation package (PSIM®) and a laboratory prototype power inverter, respectively**.

Index Terms— **Active filter, wind energy, permanent magnet synchronous generator, current controlled voltage source inverter.**

I. INTRODUCTION

Wind energy will be one of the most promising renewable energy sources in the future. This is mostly due to the fact that it is clean, pollution free and its rate of depletion is negligible. Thus, many efforts are committed into finding the most efficient approaches to exploit the wind energy into the power system [1-5]. Non-linear devices produce distorted current and voltage waveforms in the power system. The injected harmonics have several impacts on the utilities grid and loads connected to system. To overcome these power quality problems, harmonic active filters are widely used in the system. [6-11] In this paper, the analysis are focused on the system configuration with a direct coupling between the wind turbine and the active power filter employed to inject the wind power into the utility grid under fixed and various wind speed conditions. The proposed design is not only able of delivering the wind power to the grid during various wind speed conditions, but will also act as a shunt active filter to mitigate the current harmonics and regulate reactive power injected by the non-linear loads. In order to investigate and mitigate the harmonic capabilities of the WECS; a 20 kW PMSG (36 Pole) WECS simulation model was developed. The WECS is connected to a three-phase grid connected current controlled voltage source inverter (CC-VSI), which injects the extracted wind power to the grid and included with the active filter control strategies. The proposed WECS control concept is verified using a computer simulation package (PSIM®) and the CC-VSI/APF is verified using a laboratory prototype power inverter [9, 12].

II. WIND ENERGY CONVERSION SYSTEM

The WECS considered in this analysis consists of a PMSG driven by a fixed pitch wind turbine. To facilitate a grid-connected WECS, the configuration of this WECS is depicted in Figure 1. The AC-DC-AC energy conversion stages are implemented using power rectifiers and a VS-CCI. Before presenting the model descriptions and the performance of the CC-VSI/APF WECS capabilities, a brief background and description of each element in the wind energy conversion system is given.

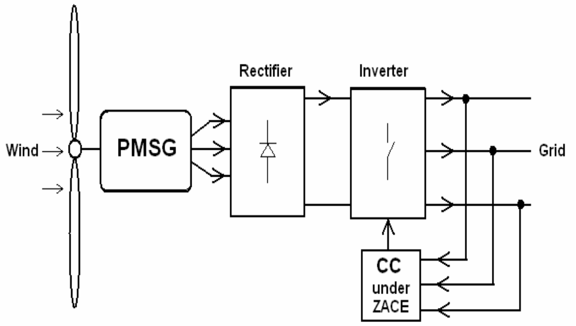

Figure 1. Wind Energy Conversion System

A. Power Generated From Wind Turbine

The mechanical power extracted from wind is given by the cube law equation (1), where power coefficient (Cp) is a function of tip speed ratio (λ) and is given in equation (2). This relationship is usually provided by the turbine manufacturer. The Cp curve that is used in this paper is shown in Figure 2. Other variables used in equation (1) are A = wind turbine swept area [m3], U_w = wind speed [m/s], ρ = air density [kg/m3], r = radius of the rotor [m] and ω_m = mechanical angular velocity of the generator [rad/sec].

$$P_m = \frac{1}{2} \cdot \rho \cdot C_P \cdot A \cdot U_W{}^3 \text{ Watts} \tag{1}$$

$$\lambda = \frac{r \cdot \omega_m}{U_W} \tag{2}$$

From equations (1) and (2), it can be seen that any change in wind speed affects the tip speed ratio and a change in tip speed ratio influences the value of Cp as well as the output of the mechanical power of the wind turbine.

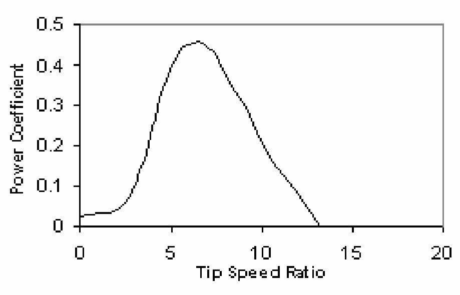

Figure 2. Power coefficient vs. Tip speed ratio

B. Three Phase VS-CCI/ APF

The three-phase VS-CCI/APF is a three-phase current controlled “voltage source inverter” with a mid-point earthed, split capacitor in the DC bus and inductors in the AC output. The VS-CCI/APF is controlled in such a way that the VS-CCI can be used to inject sinusoidal current into the grid for energy extraction from the wind turbine during linear load conditions. During non-linear load conditions, VS-CCI can be used to operate as APF for harmonic and reactive compensation [9, 11].

Under the operation as an APF, the VS-CCI provides harmonic cancellation and reactive compensation currents based on calculated reference currents from the grid. The injected currents from the WECS inverter are meant to “cancel” the harmonic and reactive currents drawn by the non-linear loads. The fundamental building block of the proposed VS-CCI/APF is shown in Figure 3. The major investigation took place at the Point of Common Coupling (PCC), where the existence of problematic harmonic from non-linear loads can be observed and therefore compensated.

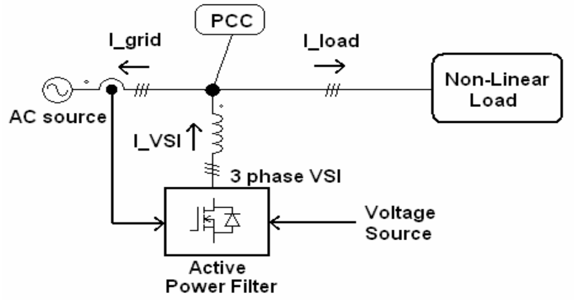

Figure 3. Fundamental building block of the VS-CCI/APF

To control the performance and the effectiveness of the filter, the CC-VSI is operated based on the concept of zero average current error (ZACE) [12, 13]. The control input is a current error signal, which, in this application, is the difference between the actual grid current and the desired or reference grid current waveform. According to the ZACE method, this error will be used to produce another signal with equal magnitude in the opposite direction as shown in Figure 4 where A represents the error signal. This will result in a zero average current error in one switching period.

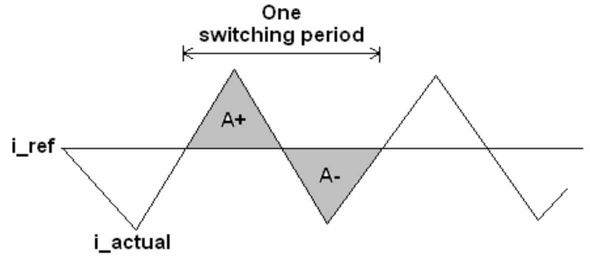

Figure 4. Current error signal under ZACE control

III. WECS AND VS-CCI/APF SYSTEM CONFIGURATION

The integration of VS-CCI/APF into the WECS is not only capable of supplying extracted wind power to the power system, but it also can significantly mitigate harmonic currents which are drawn by non-linear loads. The schematic of this design is shown in Figure 5.

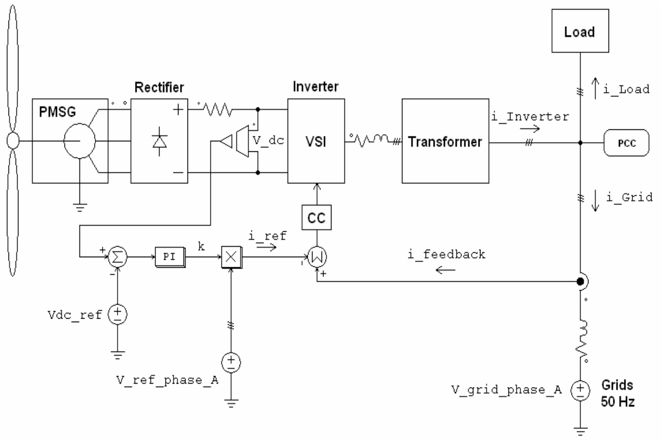

Figure 5. Integration of VS-CCI/APF WECS

As part of the APF design, reference source currents are generated in phase with voltage sources in grid for the purpose of maintaining unity power factor. To fulfil this specification, current sensors are placed on the transmission line over the grid side so that the waveform of the grid current will be forced to behave as desired. By ensuring that the grid current is sinusoidal, the APF can automatically provide the harmonic and reactive currents for non-linear loads with unity power factor as described in the following formula of the basic current summation rule at the PCC:

$$i\_Inverter(t) = i\_Load(t) + i\_Grid(t) \tag{3}$$

The existence of this relationship is proven by the simulation results in the following section. However, the direction of current flow varies depending on the amount of current generated by the WECS, which is governed by wind speed, as well as the amount of current drawn by the loads, which is fixed in this analysis. Additionally, the sinusoidal line current reference signal is given as follow:

$$i\_ref(t) = k(t) \cdot v\_ref\_phase\_A(t) \tag{4}$$

where v_ref_phase_A(t) is the fundamental component of the grid voltage and k(t) is obtained from the PI controller. The value of k determines the required magnitude of active current. This is an effective way to regulate the DC bus voltage since any mismatch between the required magnitude of active current and that being forced by the VS-CCI are compared. The 'error' from the mismatch is then treated as a control signal to manage the operation of VS-CCI.

IV. MATHEMATICAL MODEL VIRIFICATION

Figure 6 shows the test set-up and simulation results for the 20kW PMSG, 5.2m-blade radius wind turbine connected to VS-CCI with fixed voltage operation at 280V [4] .The real wind speed operation characteristics of the PMSG WECS with VS-CCI are measured in Western Australia. This value would typically be optimized knowing the Weibull distribution for wind speed at the site. In this control scheme, no additional software or hardware is needed for the CCI to vary the PMSG load line to match the maximum power line of the wind turbine generator, and results in lower conversion efficiency at wind speed above and below the optimum chosen. During variation of wind speed, this voltage is compared with the output voltage and the error is then fed to a PI controller to reduce the steady state voltage error. During the setup measurement, the WECS with VS-CCI is operating under grid connected configuration with minimum voltage and current harmonic in the system.

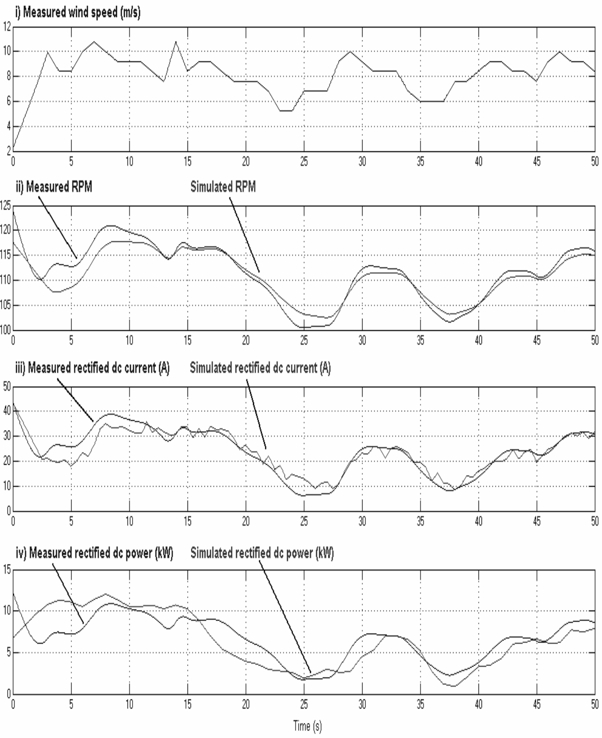

Figure 6. Test set-up and simulation results for 20kW PMSG, 5.2m-blade radius, VS-CCI grid connected fixed at 280V

In order to demonstrate the possibilities of mitigating harmonic currents, the system configuration in Figure 5 as well as the validity of the concepts discussed previously is further simulated with smaller time step simulation using PSIM®. These will provide the higher resolution simulations results of the switching and operation characteristics of the VS-CCI WECS with no-harmonic load. A constant DC reference voltage (Vdc_ref) for the APF is maintained at 280V in order to target optimum wind speed (8m/s). Figure 7 shows the WECS operating under average wind speed condition, the WECS performs like an inverter supplying sinusoidal current for injecting active power to the grid. During pure resistive and maximum wind speed operation (12.5m/s), the VS-CCI is producing the maximum output power of 20kW from the PMSG WECS. The output current from the VS-CCI is approximately 28.9A. Although there is some significant high switching harmonics generated by the inverter, it does not affect the expected performance in the grid. The results comparison has been presented to indicate the accuracy and applicability of the basic simulation model used of the PMSG-VS-CCI configuration. It will then prove to be a valuable tool between theoretical studies and the field experiments in designing a WECS.

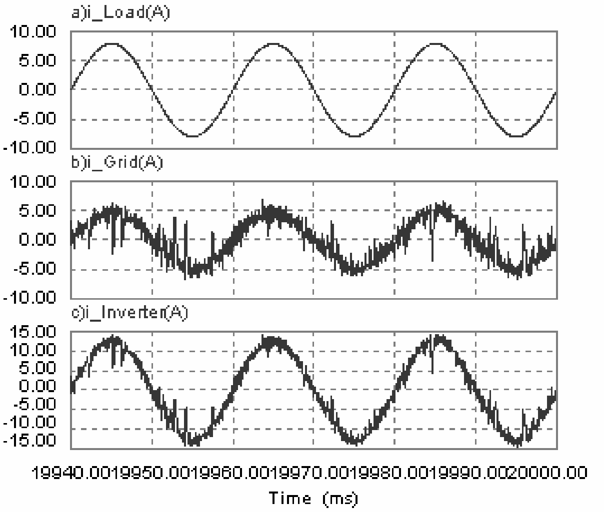

Figure 7. The AC current characteristics of (a) Harmonic-Free Load, (b) Grid and (c) Inverter at wind speed = 8 m/s.

V. PERFORMANCE OF THE SYSTEM

The output current characteristics from CC-VSI/APF are shown in the following sections. The WECS produces a 50 Hz sinusoidal current with 10 kHz harmonic due to the switching frequency in the CC-VSI.

A. Constant Wind Speed

Under the constant wind speed operation, two different scenarios are investigated to reveal performance of WECS.

1) High Wind Speed with Non-Linear Load

The first scenario is based on the simulation under high non-linear load operation with high wind speed of 8 m/s. Besides acting as an inverter, this configuration performs as an APF to cancel the low harmonic generated by the non-linear load. The waveform and spectrum can be seen in Figures 8 and 9, respectively. Especially from Figure 8, it can clearly show that the WECS-APF injects appropriate amount of current to mitigate harmonics and deliver active power to the grid.

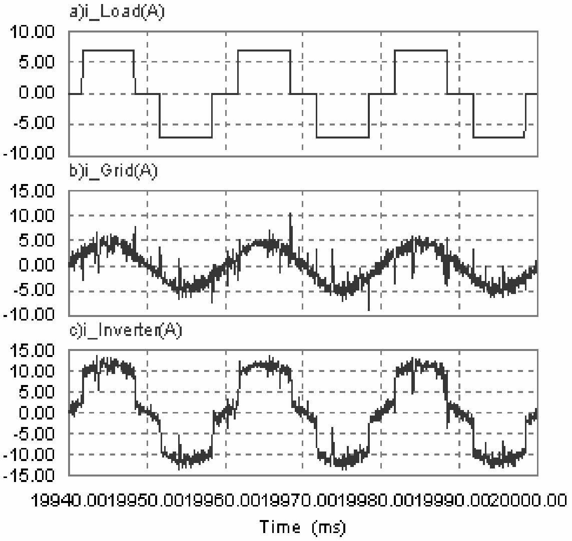

Figure 8. The AC current characteristics of (a) Non-Linear Load with Harmonics, (b) Grid and (c) Inverter at wind speed = 8 m/s.

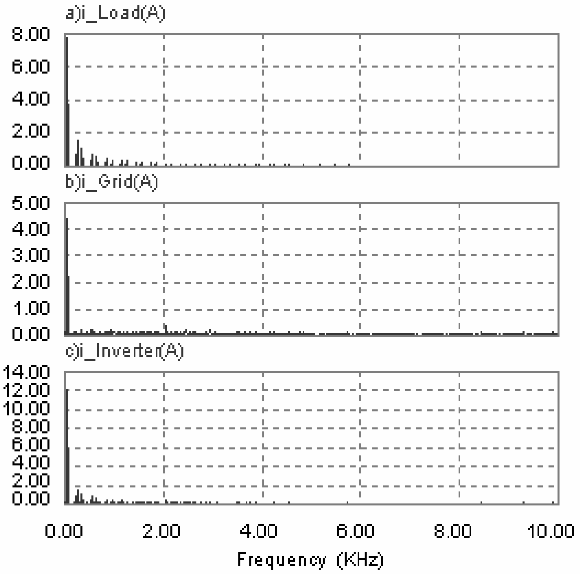

Figure 9. The AC current spectrum of (a) Non-Linear Load with Harmonics, (b) Grid and (c) Inverter at wind speed = 8 m/s.

2) *Low Wind Speed with Non-Linear Load*

When the WECS is operating at the rated cut-off wind speed, 4m/s, the wind turbine is unable to supply adequate amount of active power for both grid and non-linear load. Indeed, the WECS performs more like a shunt type APF to supply harmonic components for harmonic cancellation purposes. In order for this configuration to act as an APF, mid-pointed earthed, split capacitor in the DC bus is charged and discharged simultaneously by the grid during each switching cycle to match the required operating voltage, Vdc.

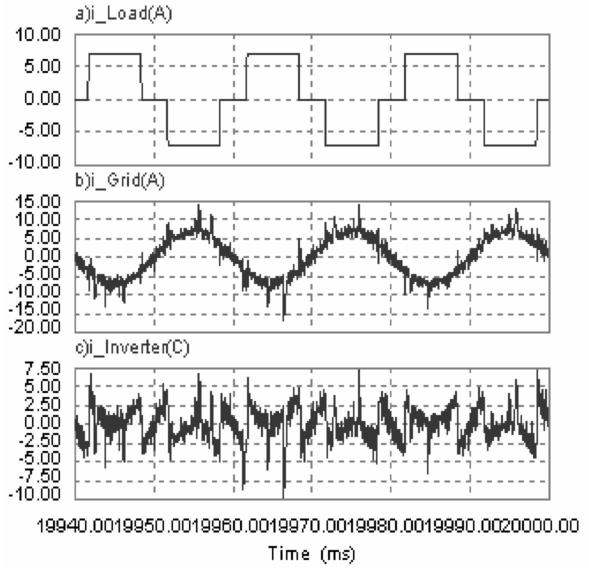

Figure 10. The AC current characteristics of (a) Non-Linear Load with Harmonics, (b) Grid and (c) Inverter at wind speed = 4 m/s.

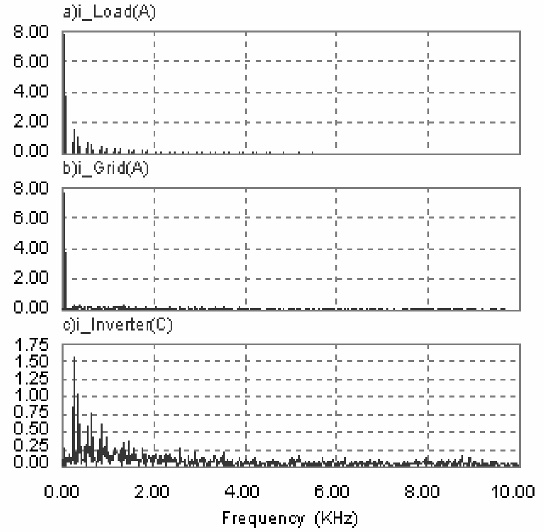

Figure 11. The AC current spectrum of (a) Non-Linear Load with Harmonics, (b) Grid and (c) Inverter at wind speed = 4 m/s.

B. *Variable Wind Speed*

In order to demonstrate the maximum potential of the WECS-APF configuration under normal site operation, simulation results are also generated under a haphazardly chosen condition of variable wind speed as shown in Figure 12. In the event, the wind speed is fluctuating with a non-uniform distribution and the output power from the inverter will not perform in a steady manner. The fluctuating output power from the VS-CCI is due to the fluctuation in power coefficient caused by varying wind speed. The APF for grid-current waveform control action is much faster than the dynamic behaviour of the wind power extraction. The active power delivered to the grid is similar to the DC power produced by PMSG through an uncontrolled rectifier. The small difference is related to the losses.

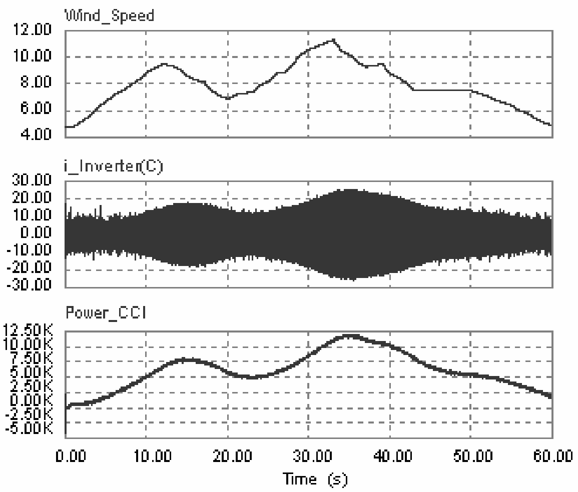

Figure 12. Output characteristics of WECS under varying wind speed.

Under high harmonic load operation, this configuration still acts as an APF to cancel the low harmonic generated by the non-linear load. Another point that should be noted from the observation is that as long as the magnitude of current from inverter is higher than the consumed current by the load, the inverter current will be injected to support grid and load as well as producing harmonic cancellation as shown in Figures 8 and 10. From the current spectrum (up to 10 kHz) in Figures 9 and 11, the lower order harmonic has been greatly reduced by the WECS VS-CCI, the spikes and the ripple produced by the inverter do not contribute significantly to the low order harmonics injected to the grid. When wind speed drops to certain level where the generated wind power do not have sufficient contribution to support the load as well as the grid on its own, like the case in Figures 10 and 11, the flow of current will, therefore, change its direction. The following equation reflects this variation with respect to equation (3):

$$i\_Load(t) = i\_Inverter(t) + i\_Grid(t) \tag{5}$$

VI. CONCLUSION

The purpose of this paper is to investigate the potential of direct coupling VS-CCI/APF and PMSG WECS and verify its capability to optimise the use of wind as a favourable energy source of the future. From the results obtained, it is proven that by using the proposed system, wind power can be efficiently extracted and harmonic currents can be mitigated. Subsequently, wind energy can potentially be the solution to the growing demand of power. Although the maximum energy available from the wind, according to equation (1), is significantly more than the active power delivered to the grid due to aerodynamic, mechanical and electrical losses in PMSG. This difference can be improved by implementing Maximum Power Point Tracking (MPPT) [5] into this system. This implementation will be done in the near future to increase the efficiency of WECS.

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