Voltage and Frequency Controller for An Autonomous Asynchronous Generator

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Abstract: A battery Energy storage system (BESS) based voltage and frequency controller (VFC), for an Autonomous Asynchronous Generator (ASG) driven by an uncontrolled pico hydro turbine used in constant power mode, is presented in this paper. Excitation of the asynchronous generator with capacitor bank enables it to generate rated voltage at no load. The additional reactive power demand of the ASG on load and that for the load itself is provided by the VFC. The proposed controller has the capability of harmonic reduction, load balancing and load leveling along with voltage and frequency control. The VFC has been realized using an IGBT based current controlled voltage source converter (CC-VSC) having a battery at its DC link. A simple and effective linear control scheme using SPWM control has been used to control the CC-VSC. This control scheme is easier to implement on hardware than the other reported schemes, as it involves only linear PI controllers. The effectiveness of the proposed controller for an autonomous generator is demonstrated by simulation on MATLAB platform.

Keywords: Autonomous Asynchronous Generator(ASG) , Voltage and Frequency Controller(VFC), SPWM control, Linear and nonlinear loads, Battery energy storage system (BESS).

I. Introduction:

The rapid depletion fossil fuel and changes in world economic environment causing the increase of the fuel cost have given thrust to research on alternative and nonconventional sources of energy. Some of the nonconventional sources of energy like micro or pico hydro generation and wind power are available at remote location and of small capacity. This called for a generator which is easy to install, cost less, easy to maintain, rugged and reliable. One generator which met all of the requirements is the induction generator [1]. Further deregulation of power system has allowed autonomous generation of electrical energy [2]-[3]. Thus autonomous asynchronous generator (AAG) with its excitation requirement being met by a capacitor bank connected across its terminals [4]-[8], has become the most suitable option. However the major hurdle in its commercialization is the poor voltage and frequency regulation. This has led to a number of attempts to investigate the voltage and frequency controllers for constant [9]–[16], as well as variable power applications [17]-[19]. The reported controllers support either three phase 3-wire or three phase 4-wire systems. The later catering for single phase loads also.

Most of the reported attempts for voltage and frequency controller for autonomous generation with induction generator are based on hysteresis control or carrier less control. In this paper an attempt has been made to achieve features similar to the above control with carrier based control or SPWM control. Such a control is inherently linear and uses PI or PID controls, which are very easy to implement in real time and are less complex in hardware than the above control. A constant power input like a Pico-hydro turbine is considered for providing input to the asynchronous generator.

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2. System Configuration

Figure 1 shows the schematic configuration of the autonomous power system being considered. A squirrel cage induction motor is operated as an asynchronous generator by a Pico-hydro turbine with constant input power. The no load excitation is provided by a delta connected capacitor bank. Consumer load both in the form linear and nonlinear loads are connected to the autonomous asynchronous generator. A battery energy storage system (BESS) based voltage and frequency controller (VFC) is connected at the point of common coupling (PCC).

When the consumer load is connected, the additional reactive power requirement of the asynchronous generator to maintain the terminal voltage is provided by the VFC. The VFC also does load leveling i.e. maintains the load on the asynchronous generator constant. If the consumer load reduces the VFC charges the battery and maintain the load on the generator constant. As the input power provided by the turbine is constant, the frequency of the system remains constant. The VFC also provides harmonic elimination and load balancing at the PCC. Any unbalance in the load either caused by single phase load or by the unbalance in the three phase load is balanced by the VFC at the PCC and is not allowed to disturb the other consumers. Thus the power quality of the consumer load is greatly enhanced.

The heart of the VFC is a three legged current controlled voltage sourced converter (CC-VSC) with a battery connected to its dc bus. The CC_VSC is connected to the PCC through inductors and resistors Lf and Rf, which can be the per phase leakage inductance and resistance of the coupling transformer. The operation of the CC-VSC is controlled by SPWM controller.

3. Sinusoidal PWM Control

The schematic diagram of the Sinusoidal PWM controller is shown in Figure 2. A high frequency carrier based sinusoidal PWM is used for generating the switching pulses for the IGBTs of the VSC [20]-[23]. This algorithm is based on the instantaneous reactive power theory. The instantaneous voltage and current of the supply system and the load are measured. The three phase system is transformed to a synchronously rotating reference frame using Park’s transformation [24] [25]. The compensation is achieved by control of id and iq.

The instantaneous id reference current is generated by PI regulation of the dc terminal voltage with respect to a reference dc voltage. Similarly iq reference current is generated by PI regulation of the ac terminal voltage of the VSC with respect to a reference ac terminal voltage [22][23]. The decoupled id and iq components obtained from abc to dq transformation of the measured instantaneous three phase current, are then regulated with two separate PI regulators with respect to the reference id and iq currents obtained earlier. In order to synchronize the abc to dq0 transformation a Phase Locked Loop (PLL) is used.
4. Algorithm for Modelling of Carrier Based Control of DSTATCOM

The control of VSC shown in Figure 2, is modeled in discrete mode using ode23tb on MATLAB platform [26]. The discrete-time integrator block [27] is used to implement the PI controller. Forward Euler method is used for integration. The discrete-time integrator block approximates $1/s$ by $T/(Z-1)$, which results in the following expression for the output $Y(n)$ at the $n^{th}$ step:

$$Y(n) = Y(n-1) + KT \cdot U(n-1) \quad (1)$$

Where $U(n-1)$ is the input to the controller at the $(n-1)^{th}$ step. $T$ is the discretization time interval.

(1) PCC terminal Voltage Control

The three phase supply voltage ($v_{sa}$, $v_{sb}$, and $v_{sc}$) are considered sinusoidal and hence their amplitude is computed as:

$$V_i = \sqrt{\frac{2}{3} (v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \quad (2)$$

The $V_i$ computed above is compared with the desired terminal voltage $V_{tref}$. The ac voltage error $V_{er(n)}$ at the $n^{th}$ sampling instant is

$$V_{er(n)} = (V_{tref} - V_{t(n)}) \quad (3)$$

Where $V_{t(n)}$ is the amplitude of the sensed three phase ac voltage at the PCC terminal at the $n^{th}$ instant. The error $V_{er(n)}$ is fed to an outer PI controller, using discrete time integration, to generate the $I_{qref}$.

$$I_{qref(n)} = I_{qref(n-1)} + K_{ap} \cdot \{V_{er(n)} - V_{er(n-1)} \} + K_{ai} \cdot V_{er(n)} \quad (4)$$

Where $K_{ap}$ and $K_{ai}$ are the proportional and integral gain constants of the outer PI controller of the ac terminal voltage at the PCC.

The actual $I_q$ is generated by an ‘abc to dq convertor using parks transformation over the load current. The $I_{qref}$ and $I_q$ are compared and the error is fed to an inner PI current controller to generate $V_q$. 

Figure 2. Schematic diagram for Sinusoidal PWM control
\[ I_{qer}(n) = (I_{qref}(n) - I_q(n)) \]  

(5)

\[ V_{q}(n) = V_{q(n-1)} + K_{bp} \{I_{qer}(n) - I_{qer(n-1)}\} + K_{bi} I_{qer(n)} \]  

(6)

Where \( K_{bp} \) and \( K_{bi} \) are the proportional and integral gain constants of the inner PI controller of the ac terminal voltage at the PCC.

(2) Control of the Voltage at the dc terminal of the VFC

The dc voltage error \( V_{derr(n)} \) at the \( n \)th sampling instant is computed by comparing the \( V_{dc} \) of the dc bus with the desired dc bus voltage \( V_{dc\_ref} \).

\[ V_{derr(n)} = (V_{dc\_ref} - V_{dc(n)}) \]  

(7)

Where \( V_{dc(n)} \) is the sensed dc voltage at the dc bus of the VFC at the \( n \)th instant.

An outer PI controller uses the dc voltage error \( V_{derr(n)} \) to generate the \( I_{dref} \).

\[ I_{dref}(n) = I_{dref(n-1)} + K_{ap} \{V_{derr(n)} - V_{derr(n-1)}\} + K_{ai} V_{derr(n)} \]  

(8)

Where \( K_{ap} \) and \( K_{ai} \) are the proportional and integral gain constants of the outer PI controller of the dc bus voltage.

The actual \( I_d \) is generated by an ‘abc to dq’ converter using Parks transformation over the load current. The \( I_{dref} \) and \( I_d \) are compared and the error is fed to an inner PI current controller to generate \( V_d \).

\[ I_{derr(n)} = (I_{dref(n)} - I_d(n)) \]  

(9)

\[ V_{d(n)} = V_{d(n-1)} + K_{bp} \{I_{derr(n)} - I_{derr(n-1)}\} + K_{bi} I_{derr(n)} \]  

(10)

Where \( K_{bp} \) and \( K_{bi} \) are the proportional and integral gain constants of the inner PI controller of the dc bus voltage.

(3) PWM current Controller

The \( V_d \) and \( V_q \) signals generated above are converted into modulation index ‘\( m \)’ and phase ‘\( \Phi \)’ which are then used by the PWM modulator for producing the required pulses for firing the IGBTs of the VSC. This causes the VSC to maintain the terminal voltage of the generator by generating / absorbing the required reactive current and supplying / absorbing active power from the generator to charge the battery and maintain the dc side voltage of the converter.

5. Design of BESS

The battery has been modeled by its Thevenin equivalent circuit [28] [31] and has been represented as such in Fig.1 & 2. \( V_{dc} \) is the dc bus voltage, \( V_{oc} \) is the no load open circuit voltage of the battery, \( R_2 \) is the internal resistance and the over voltage condition is represented by the parallel combination of \( R_1 \) and \( C_1 \). The resistance \( R_2 \) is usually small. Since the self discharging current of a battery is small, the value of \( R_2 \) is large. The terminal voltage of the battery [32] is given by

\[ V_b = \frac{(2\sqrt{2}V_{rms})}{\sqrt{3}m} \]  

(11)
‘m’ is the modulation index, with a maximum value of 1. \( V_{\text{rms}} \) is the line voltage on the ac side of VSC.

Energy stored in the battery is measured in kWh. The equivalent capacitance of the battery model can mathematically represented by

\[
C_1 = \frac{(kWh \times 3600 \times 10^3)}{0.5(V_{oc_{\text{max}}}^2 - V_{oc_{\text{min}}}^2)}
\]  

(12)

\( V_{oc_{\text{max}}} \) and \( V_{oc_{\text{min}}} \) are the maximum and the minimum open circuit voltage of the battery during its operation. From the above equations, different parameters of the battery are selected and are given in the Appendix.

Figure 3 shows the MATLAB based simulation model of the AAG along with its controller. A 4kW, 415V, 50Hz, 4-pole, Y-connected asynchronous machine is used for autonomous operation. Data for characteristics of the machines are obtained simulation of saturation and are given in the Appendix and are used in the model. The simulation is performed on MATLAB platform (version 7.1) in discrete mode at 5 \( \mu \)sec step size with ode 23tb (stiff/TR-BDF-2) solver.

6. Results and Discussions:

The performance of the proposed controller for an autonomous asynchronous generator is observed when subjected to balanced/ unbalanced linear and nonlinear loads. Simulated and transient waveforms of the generator voltage \( (V_{abc_{B4}}) \), generator currents \( (I_{abc_{B4}}) \), consumer load current \( (I_{abc_{B3}}) \), controller current \( (I_{abc_{B2}}) \), controller bus voltage \( (V_{abc_{B2}}) \), battery voltage \( (V_{dc}) \), Battery current \( (I_{dc}) \), speed of asynchronous generator \( (w) \), and total harmonic distortion at the PCC (THD \( V_{a_{B4}} \)) at different dynamic conditions are shown in Figure4 and Figure5 for linear and non linear loads respectively. The simulation demonstrates the voltage and frequency control aspect, load balancing and load leveling aspect and the harmonic elimination aspect of the VFC. Parameters of the asynchronous generator considered, is presented in Appendix. Figure6 and Figure7 demonstrate the harmonic spectrum of source voltage and current with balanced / unbalanced linear and non linear loads.

A. Performance of AAG with BESS based VFC Feeding linear load

Figure 4 demonstrates the performance of the BESS based VF controller for an AAG with balanced / unbalanced R-L loads. The system starts with a static load of 1kW on generator bus and no load on consumer bus. Load is applied on the consumer load bus at 0.5 sec. However the generator bus current remains constant. The increased load is supplied by the controller, represented by increased battery current \( I_{dc} \). This demonstrates the load leveling aspect of the VFC. The consumer load is 1kW and 200 VAr per phase, i.e. a total 3 phase load of 3kW and 600 VAr.

Figure 3. MATLAB based simulation model of an autonomous asynchronous generator with BESS based voltage and frequency controller.
The consumer load is delta connected. At 0.55 sec one phase is opened and at 0.6 sec another phase is opened creating an unbalanced load. Again the phases are reconnected at 0.65 sec and 0.7 sec making the load again balanced. The VFC maintains the generator voltage and current constant, which shows the load balancing aspect of the BESS based VF controller. Load is removed from the consumer load bus at 0.8 sec. After removal of the consumer load at 0.8 sec the battery again starts charging with generated power of AAG. This demonstrates that the BESS based VF controller maintains the load on the generator bus constant and thus it is able to regulate the generator speed and hence the system frequency constant. During the entire simulation the speed (w) of the asynchronous generator is maintained almost constant at 1500 rpm. All through the simulation the generator bus voltage remains constant, which demonstrates that the VFC supplies the dynamic reactive power requirement of the
asynchronous generator and that of the load. This demonstrates the voltage control aspect of the VFC. The graph of the THD $V_{a_b d}$ shows that the VFC is capable of reducing the harmonics generated by the load and the converter and maintain the THD of the generator bus voltage at around 3%.

Figure 5b. Harmonic spectrum of AAG source current with balanced linear Load.

Figure 5c. Harmonic spectrum of AAG source voltage with unbalanced linear Load.
Figure 5d. Harmonic spectrum of AAG source voltage with unbalanced linear Load.

Figure 5e. Harmonic spectrum of VFC dc link voltage with balanced linear Load.

Figure 5a to 5f demonstrate the harmonic spectrum of the source voltage $V_{aB4}$ source current $I_{abcB4}$ and of the voltage $V_{dc}$ of the dc link of VFC with balanced and unbalanced linear load and that of voltage of the dc link. The total harmonic distortion of the voltage is very small. The VFC reduces the harmonics at PCC due to the consumer loads and due to VSC to within that specified by IEEE 519 standards.
B. Performance of AAG with BESS based VFC Feeding nonlinear load:

Figure 6 demonstrates the performance of the BESS based VF controller for an AAG feeding balanced/unbalanced nonlinear load. The system starts with a static load of 1kW on generator bus and 1.5 kW dc load on consumer bus. The dc load is created by a 3 phase uncontrolled bridge rectifier having a resistive load on its dc side. The total load is partly supplied by the asynchronous generator and partly by the VFC. The generator bus current is maintained constant. The current of the load bus $I_{abc_{B3}}$ is seen as highly nonlinear. However current of the generator bus $I_{abc_{B4}}$ is seen to remain sinusoidal. The graph of the THD $V_{a_{B4}}$ shows that the VFC is capable of reducing the harmonics generated by the load and the converter and maintain the THD of the generator bus voltage at around 3.5% when the nonlinear load is connected.
At 0.6 sec one phase connected to the load is opened and creating an unbalance in the load current. The phase is reconnected at 0.7 sec making the load again balanced. The unbalance in the load current produces little effect on the voltage and current of the generator bus. However the THD of the generator voltage is increased to 4%. The VFC maintains the generator voltage and current constant, which shows the load balancing aspect of the BESS based VF controller. Consumer Load is removed from the consumer load bus at 0.8 sec. After removal of the load at 0.8 sec the battery starts charging with extra generated power of the Asynchronous generator. It is shown by the change in the battery current. This demonstrates that the BESS based VF controller maintains the load on the generator bus constant and thus it is able to regulate the generator speed and hence the system frequency constant. The THD is reduced to 3%. This demonstrates the load leveling aspect of the VFC. During the entire simulation the speed (w) of the asynchronous generator is maintained almost constant at 1500 rpm. All through the simulation the generator bus voltage remains constant, which demonstrates that the VFC supplies the dynamic reactive power requirement of the asynchronous generator. This demonstrates the voltage control aspect of the VFC.

Figure 7a. Harmonic spectrum of AAG source voltage with balanced nonlinear Load.

Figure 7b. Harmonic spectrum of AAG source current with balanced nonlinear Load.
Figure 7c. Harmonic spectrum of AAG source voltage with unbalanced nonlinear load.

Figure 7d. Harmonic spectrum of AAG source current with unbalanced nonlinear load.

Figure 7a to 7f present the harmonic spectrum of the source voltage \( V_{ab} \), source current \( I_{abc} \) and of the voltage \( V_{dc} \) of the dc link of VFC with balanced and unbalanced nonlinear load and that of voltage of the dc link. The total harmonic distortion of the voltage is very small. The VFC reduces the harmonics at PCC due to the consumer loads and due to VSC to within that specified by IEEE 519 standards.
7. Conclusion

The performance of battery energy storage system based voltage and frequency controller for an autonomous asynchronous generator has been demonstrated for load leveling, voltage and frequency regulation. The VF controller proposed has also been demonstrated to have good capability for harmonic elimination and load balancing. These features of the VFC have been achieved using a simple and linear SPWM control of the CC-VSC. The SPWM control has been achieved with PI controllers. This SPWM control is much easier to implement in hardware design than other reported schemes. The simulation of the proposed controller establishes that the proposed VFC shall perform satisfactorily for an autonomous system feeding both balanced and unbalanced linear and nonlinear loads.
APPENDIX:
Asynchronous Generator:
4 kW, 415 V, 50 Hz, rpm = 1440, Squirrel cage, Pole Pair = 2,
\( R_s = 0.435\, \Omega, \quad R_r = 0.816\, \Omega, \quad L_s = 0.004\, H, \quad L_r = 0.002\, H, \quad L_m = 69.31\, mH, \quad \text{Inertia } J = 0.089\, \text{kg}\cdot\text{m}^2 \)
No load excitation capacitor bank, delta connected, each of 550\,\mu F.
Prime Mover Characteristics
\( T_{sh} = k_1 - k_2\omega, \quad k_1 = 3100, \quad \text{and } k_2 = 2. \)

DSTATCOM parameters :
\( L_f = 800\, \mu H, \quad R_f = 0.004\, \Omega, \quad \text{and } R_2 = 0.1\, \Omega, \quad R_i = 10k\, \Omega, \quad C_s = 25000\, \text{F}, \quad C_{dc} = 1500\, \mu F, \quad K_{ap} = 5, \quad K_{bi} = 20 \)
\( K_{bp} = 0.05, \quad K_{bi} = 2. \)

8. References:
[27] Help file Discrete time integrator block MATLAB 7.1
Ambar Nath Banerji received B.E. degree in electrical engineering from University of Roorkee, India and M.E. degree from University of Rajasthan, India. He has 22 years of experience in control systems of various process industries like power plants, steel industries and chemical plants. He is presently associated with the Electrical Department of Meghnad Saha Institute of Technology Kolkata. His field of interest include, power electronics, power systems, static VAr compensation. He is member of IEEE, a life member of Institution of Engineers (India) and a member of Association of Computer Electronics and Electrical Engineers.

Sujit Kumar Biswas received the B.E.E. degree (with Honours) in Electrical Engineering from Jadavpur University, Kolkata, in 1978 and then the M.E. degree (with Distinction) in Electrical Engineering from the Indian Institute of Science, Bangalore. Since then, he was employed in the Department of Electrical Engineering, Indian Institute of Science, Bangalore, during a period in which he received PhD. He joined the faculty of the Department of Electrical Engineering, Jadavpur University, Kolkata, in 1987 as a Reader, where he is currently a Professor. He has served as the Head of the Department of Electrical Engg, Jadavpur University.

His fields of interest are static power conversion, electrical drives, power semiconductor applications, magnetics and applied electronics. He has authored 33 research publications in refereed journals [of which 8 are in IEEE Transactions and 3 in IEE Proceedings (now IET Journals)] and 62 papers in National and International Conferences (of which 48 are in IEEE Conferences) and about 42 circuit ideas/popular electronics articles. He also holds two patents on Semiconductor Power Converter Circuits and has applied for a patent on a special generator.

He has been a member of several National and International Committees and has served as an External Expert to several Government of India organizations.

Dr. Biswas received several awards, amongst which the most prestigious are the Indian National Science Academy Medal for young Scientists in 1987 and the IETE-Bimal Bose Award for “Outstanding contribution in the field of Power Electronics” in 2004.

He is a Life member of the Solar Energy Society of India, a Fellow of the Institution of Engineers (India), a Fellow of the Institution of Electronics and Telecommunication Engineers (India) and a Senior Member of the Institution of Electrical & Electronics Engineers (USA).

His name is recorded on the panel that finalized the IEEE Standard 519–1992 : “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”. One Research Paper on gate drive technique for IGBT is referred in the Application Notes for IGBTs by two major international manufacturers – International Rectifier and ST-Microelectronics. Has been associated as a consultant with several major industries in India to develop indigenous technologies in the area of Power Electronics and Drives.

Bhim Singh was born in Rahmanpur, India, in 1956.He received the B.E. degree in electrical engineering from the University of Roorkee, Roorkee, India, and the M.Tech. degree in power apparatus and systems, and the Ph.D. degree from the Indian Institute of Technology, New Delhi, India, in 1977, 1979, and 1983, respectively. In July 1983, he joined the Department of Electrical Engineering, University of Roorkee, as a Lecturer, becoming a Reader in March 1988. In December 1990, he became an Assistant Professor and, in February 1994, an Associate Professor in the Department of Electrical Engineering, Indian Institute of Technology, New Delhi, India. Since August 1997, he has been a Professor. He has authored more than 200 research papers in the areas of power electronics,
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