Battery-supported unified power quality controller for small hydro-based isolated power generation

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Abstract
In this paper, a battery-supported unified power quality controller (UPQC) for a small hydro-based isolated power generation is investigated as a voltage and frequency controller. The self-excited squirrel cage induction generator driven by constant power prime mover (small hydro turbine) has unacceptable voltage, frequency and power quality under non-linear loads. The battery-supported UPQC-based voltage controlled-voltage source converter is designed, modelled and simulated in MATLAB environment. Here UPQC has series and shunt converters with a battery and it is used to feed the local loads. This small distributed power generation system is capable to feed unbalanced non-linear loads because a shunt converter is used to take care the compensation of unbalanced loads and it always maintains the source currents balanced and sinusoidal. Moreover, a series converter is used to inject the series voltages in the self-excited squirrel cage induction generator terminals to regulate the common coupling point voltage during unbalanced non-linear loads. Performance of a battery-supported UPQC is also validated experimentally using a laboratory prototype of a 3.7 kW, 230 V, 50 Hz capacitor excited induction generator.

1 | INTRODUCTION

The conventional power plants are producing the electrical power through fossil fuels that are limited in availability. The fossil fuel hazard for environment is a big challenge with respect to global warming. The power producers that generate the power through conventional sources, are restricted for payback to reduce carbon emission. Thereby every agency has tried to promote electrical power generation through renewable energy sources (RESs) such as biogas, biomass, small hydro, wind, solar etc. All these power generation sources produce power at lower rating and may be used locally by the distributed generation. The power generated at the load centre directly transferred to the loads without connecting the main grid, is called distributed power generation. The power generated at the load centre directly transferred to the loads without connecting the main grid, is called distributed power generation. Normally coils field synchronous generator is used to generate the power in conventional power plant from different energy sources. The synchronous generator is bulky in size and requires frequent maintenance due to slip rings, coils field rotor and excitation system. That is why an induction generator is recommended for distributed power generation. A doubly fed induction generator also has coil field rotor whereas squirrel cage induction generator (SCIG) has rugged construction and brushless rotor, thereby requires less maintenance and cost. A squirrel cage induction generator excited with external excitation capacitor bank is called SCIG. However, the main problem with SCIG feeding three-phase loads is the reactive power, an unbalance, which is not capable to regulate the constant terminal voltage to supply continuous power [1–3].

The SCIG is used with the constant speed prime mover such as biomass, diesel and gas turbines driven power generation, where the problem of unacceptable voltage regulation exists at different load conditions. The small hydro is an almost constant power prime mover to drive SCIG, which has problems of poor frequency regulation at different loading conditions [4]. It is also having problems of unacceptable voltage regulation and power quality at different nature of linear and non-linear loads. The voltage regulating device such as static compensator (STATCOM), dynamic voltage restorer (DVR), switching reactor, switching capacitor, static shunt compensator and series compensators are used to maintain source voltages and power quality improvement of source voltages and currents at linear
and non-linear loads [5–7]. Further, a battery-connected voltage and frequency controller has been designed for reactive and active power balance for a constant source voltage and frequency in [8–10]. The electronics load controllers (ELCs) have been designed to maintain constant frequency with constant power flow from SCIG [11]. The small hydro is an almost constant power drive requires the load power to be maintained at constant value under different load conditions with the use of a dump load or an energy storage that connected in parallel called electronic load controller (ELC) [12]. Similarly, substantial literature [13, 14] is available on shunt filter control techniques for point of common coupling (PCC) voltage and frequency regulation. Although the presented shunt compensator is robust and capable to regulate the PCC voltage as well frequency. However, when only a shunt compensator is used to regulate the PCC voltage, the SCIG terminal voltage is equal to the PCC load voltage, which leads to saturation in the SCIG. If load voltage requirement is more than the SCIG terminal voltage rating, under such condition, the SCIG with a shunt compensator is not a good solution. Moreover, if SCIG voltage is little lower than the PCC voltage then it comes out of saturation. In this condition, its magnetizing current is reduced drastically [15]. In addition, its voltage harmonics are reduced. This SCIG is found capable of generating increased power and results in the reduction in core losses. It also enhances its efficiency and reduces the losses less than rated condition and an increased power generation. However, the terminal voltages of SCIG are reduced, it is deteriorated the stability because SCIG has tendency to lose the self-excitation under this lower level of saturation. In this work, the series converter of UPQC is found capable to regulate PCC voltages at rated value under variety of loads. Moreover, the stability of this system is also enhanced due to closed loop control of it.

Hence in this paper, a small hydro-based distributed power generation system is developed to feed varying unbalanced non-linear loads while UPQC with battery energy system (BES) is used as its voltage and frequency controller.

In this work, an attempt is made on an insulated gate bipolar transistors (IGBTs) based solid state static unified power quality controller (UPQC) with a battery support at DC bus for constant power small hydro turbine driven generator by feeding three-phase unbalanced non-linear loads. The battery is able to maintain constant frequency with active power balance at reduced rated load with stored energy in it. In case of more than rated load conditions, the battery provides the stored energy to the load for maintaining active power balance and its frequency. The battery-supported solid state UPQC with a capacitor at its DC bus is also able to maintain constant voltage and frequency at different linear, non-linear and unbalanced load conditions. The battery-supported UPQC connected in series as well as shunt with the SCIG system has the capabilities of both voltage and frequency control at non-linear unbalanced loads while compensating its harmonics and unbalances. The series-connected VSC of UPQC injects the compensation voltages at the PCC and maintains the PCC load voltages as per the load requirement irrespective of SCIG terminal voltages. Moreover, the shunt compensator compensates the load reactive power and fulfills the load other requirements such as harmonics and unbalances.

The proposed battery-supported UPQC for the SCIG system feeding a non-linear unbalanced load, is designed, modelled and simulated in MATLAB platform. The experimental validation of the battery-supported UPQC for SCIG feeding non-linear unbalanced loads is realised in the laboratory.

This work on a small hydro power generation using SCIG and controlled with UPQC has the following features.

- The battery-supported UPQC is designed, modelled, simulated and experimental-validated for small hydro-based SCIG system.
- The battery-supported UPQC is able to regulate the PCC voltage and frequency with harmonics elimination at different non-linear unbalanced loads.
- Here series and shunt VSCs of a battery-supported UPQC are used to provide dynamic reactive power as well as balance the active power in an islanded generation system.
- The shunt VSC is a multifunctional converter, which provides load harmonics current elimination, improvements of the source current THDs and compensates the load reactive power and load negative sequence currents.
- The series compensator is used to regulate the load PCC voltage at its desired value. However, the SCIG terminal voltage is different value and independent with the load voltage.
- Moreover, the series converter is used to improve the voltage profile at the loads and it also shares part of reactive power of the SCIG and loads.

2 | SCHEMATIC OF SCIG SYSTEM

An induction machine is used as an SCIG, where a 3-phase excitation capacitor bank is providing required reactive power to produce no-load base voltage. The battery-supported UPQC has its own active as well as reactive power control with the battery and the DC link capacitor, respectively, which is able to improve voltage, frequency and power quality of SCIG system at loaded condition. Figure 1 shows a schematic diagram of SCIG, a battery-supported UPQC and non-linear loads. The
battery-supported UPQC is a combination of shunt and series VSCs. Moreover, as shown in Figure 1, the higher order harmonics of voltages and currents are eliminated using the ripple filters connected at series and shunt converters, respectively. As depicted in Figure 1, a series VSC is connected in between PCC and SCIG output three phase terminals. The shunt converter is connected through interfacing inductors and its purpose is to reduce the ripple currents from the shunt VSC currents.

3 CONTROL STRATEGIES

The control of shunt VSC is shown in Figure 2 and Figure 3 shows the control of series VSC.

3.1 Control strategy of shunt converter

The control strategy of shunt VSC is based on synchronous reference frame (SRF) theory to improve the power quality of SCIG at the non-linear loads.

The three-phase load currents are transforming in d-q-0 reference frame by Park’s transform. The 3-phase load voltages are passed through phase locked loop (PLL) to synchronize signals. The final active component of reference source current \( I_{sd}^* \) is generated by difference between active component of load current \( I_{ld} \) and the output of the PI frequency controller \( I_{df} \). The steady state DC value of the active load current component \( I_{ld} \) is generated through low pass filter. The final active component of reference SCIG source current \( I_{sd}^* \) is calculated as

\[
I_{sd}^* = I_{df} - I_{ld} \tag{1}
\]

where \( I_{df} \) is a reference output of the PI controller, which is generated from the difference between reference and real frequency signal fed to the PI controller.

The reactive current of reference source current is calculated by difference between reactive components of load currents and the reference reactive current component \( I_{qr}^* \) that is generated through a voltage PI controller with its input as the difference between reference and sensed SCIG source voltage amplitude. The DC value of the reactive component of the load current \( I_{qr} \) is generated through a low pass filter. The final reactive component of reference source current \( I_{qr}^* \) is calculated as

\[
I_{qr}^* = I_{qr} - I_{q} \tag{2}
\]

The reference source currents \( i_{sa}^*, i_{sb}^*, i_{sc}^* \) are estimated from final active component of reference source current \( I_{sd}^* \) used as a-axis component and final reactive component of reference source current \( I_{qr}^* \) used as q-axis component that are converted into three-phase signals by using an inverse Park’s transformation.

The error signals of difference between estimated \( \hat{i}_{sa}, \hat{i}_{sb}, \hat{i}_{sc} \) and sensed source currents \( i_{sa}, i_{sb}, i_{sc} \), which are input signals for the hysteresis controller to produce switching pulses for IGBT’s shunt VSC.

3.2 Control strategy of series converter

This control strategy for a series converter is shown in Figure 3. Here, the three-phase load voltages \( v_{La}, v_{Lb}, v_{Lc} \) are compared with reference three phase load voltages to regulate at constant value irrespective of fluctuations. As depicted in Figure 3, the series converter pulses are generated through the hysteresis controller. Moreover, as depicted in Figure 3, the reference load voltages are generated using the in-phase unit component. The in-phase unit templates are estimated as [2],

\[
\begin{align*}
\hat{u}_{pa} &= \frac{v_{La}}{V_{ml}}, & \hat{u}_{pb} &= \frac{v_{Lb}}{V_{ml}}, & \hat{u}_{pc} &= \frac{v_{Lc}}{V_{ml}}
\end{align*}
\tag{3}
\]

where \( v_{La}, v_{Lb} \) and \( v_{Lc} \) are phase voltages, which are estimated through sensed line voltages. Phase voltages are estimated as

\[
\begin{align*}
v_{La} &= \frac{1}{3} (2v_{Lad} + v_{Lbc}), & v_{Lb} &= \frac{1}{3} (-v_{Lad} + v_{Lbc}), & v_{Lc} &= \frac{1}{3} (-v_{Lad} - 2v_{Lbc})
\end{align*}
\tag{4}
\]

Moreover, the load voltage amplitude is estimated as [2],

\[
v_{ml} = \sqrt{\frac{2}{3}} \sqrt{\frac{2}{3} \left( v_{Lad}^2 + v_{Lbd}^2 + v_{Lbc}^2 \right)}
\tag{5}
\]
4 \hspace{0.5em} RESULTS AND DISCUSSION

The constant power prime mover such as small hydro-driven SCIG supplying power to the non-linear loads with a battery-supported UPQC is demonstrated and waveforms of SCIG supply voltages ($v_s$), supply currents ($i_s$), load voltages ($v_L$), load currents ($i_L$), compensation currents ($i_c$), a battery currents ($I_{batt}$), the DC link voltage ($V_{dc}$) and the frequency ($f$) are shown in Figures 4–11.

4.1 \hspace{0.5em} Simulated performance of SCIG-based system

Figure 4(a) shows the performance of a battery-supported UPQC with a SCIG system at non-linear load condition. The load of phase $b$ is disconnected at 1.0 s. Figure 4(b) shows the performance of a battery-supported UPQC with SCIG system at unbalanced load condition. These results show performance of a battery-supported UPQC with a SCIG system at non-linear load. That battery-supported UPQC is able to regulate the SCIG source voltages with improved power quality of SCIG source voltages, load voltages and source currents under both conditions.

The battery-supported UPQC is also found capable to achieve the constant frequency and the DC link voltage. The harmonics spectrum of load current ($i_L$), SCIG supply voltage ($v_s$) and supply current ($i_s$) of battery-supported UPQC with SCIG system at non-linear load, are shown in Figure 5(a–c), respectively. The battery-supported UPQC is also capable to maintain total harmonics distortion (THD) of the SCIG source currents and the SCIG voltage at non-linear loads in acceptable limit of 5% as per the IEEE standard. Figure 6(a,b) shows the behaviour of load voltage and SCIG terminal voltage during steady state and at load perturbation condition.

4.2 \hspace{0.5em} Experimental performance of SCIG-based system

Performance of this battery-supported UPQC with an SCIG feeding non-linear loads, is also verified experimentally on a prototype of it in the laboratory as shown in Figure 7. Its prototype consists of a 3.7 kW, 230 V, 50 Hz, $Y$-connected SCIG and a delta-connected capacitor bank to provide required reactive power for developing rated SCIG voltage at no load. The constant speed prime mover characteristic for driving the SCIG is developed by an adjustable speed AC motor drive. The DC link voltage ($V_{dc}$), the SCIG supply voltages ($v_{sab}$, $v_{sbc}$), source currents ($i_{sa}$, $i_{sb}$) and load currents ($i_{La}$, $i_{Lb}$) are sensed through voltage and current sensors. The host personal computer (PC) is used to implement control schemes of battery-supported UPQC and to generate gate pulses of VSCs through DSP-dSPACE. The power analyser and digital storage oscilloscope (DSO) are used to record the supply voltage ($V_s$), supply current ($i_s$), load voltage ($V_L$), load current ($i_L$), compensation voltage by series VSC, compensation current by shunt VSC and the DC link voltage ($V_{dc}$) at unbalanced non-linear load. Figure 8(a–f)
shows the power quality of SCIG source voltage, source current, the load voltage, load current with THD of source current, load voltage and load current under non-linear load condition. These results show an improved quality of SCIG supply current, SCIG voltage and load voltage at non-linear load in the acceptable limits. Figure 8(a,b) shows SCIG supply voltage ($v_s$), load voltage ($v_L$), series VSC voltage ($v_c$), supply current ($i_s$), load current ($i_L$) and compensation current ($i_c$) for a battery-supported UPQC with SCIG system at a non-linear unbalanced load, respectively. The battery-supported UPQC injects a set of compensation voltages in series between SCIG source and load voltages for maintaining constant load terminal voltage with power quality improvement, which shows the series compensation operation. Simultaneously, the battery-supported UPQC injects the compensation currents in the SCIG supplying power to non-linear loads in order to eliminate harmonics of SCIG source currents at unbalanced and non-linear loads, which shows the shunt compensation operation. The battery-supported UPQC is found capable to maintain constant load voltage even at reduced SCIG source voltage as shown in Figure 9. Figure 10 shows waveforms of source current ($i_s$), load current ($i_L$), load voltage ($V_L$), SCIG source voltage ($V_s$), bat-
FIGURE 8  Steady state performance of battery-supported UPQC (a) $v_1$ and (b) $i_1$. Harmonic spectrum of (c) $i_1$, (d) $v_L$, and (e) $i_L$. Harmonic spectrum of (f) $P_v$.

FIGURE 9  Performance of a battery-supported UPQC at non-linear load; (a) at non-linear load condition, (b) at load unbalanced condition

FIGURE 10  Performance of a battery-supported UPQC with SCIG system at unbalanced load condition (a) $i_{batt}$, $i_L$, $V_s$ and $V_L$ under load removal (b) $i_{batt}$, $i_L$, $V_s$ and $V_L$ under load addition (c) $i_{batt}$, $i_L$, $V_s$ and $V_L$ under load removal

ttery current ($i_{batt}$), amplitude of SCIG source voltage ($V_s$) and amplitude of load voltage ($V_L$) at unbalanced load. These waveforms of the battery current ($i_{batt}$), the load current ($i_L$), SCIG source voltage ($V_s$) and load voltage ($V_L$) are shown in Figure 10(a,b) with removal and addition of one phase load current, respectively.

The waveforms of SCIG source current ($i_s$), load current ($i_L$), SCIG source voltage ($V_s$) and load voltage ($V_L$) are shown in Figures 10(c) and 11(a) with removal and addition of one phase load current, respectively. The waveforms of source current ($i_s$),
load current ($i_L$), amplitude of SCIG source voltage ($V_S$) and amplitude of load voltage ($V_L$) at removal and at reconnection of one phase load current, are shown in Figure 11(b). The battery-supported UPQC is found capable to maintain constant load terminal voltage even at reduced and above than rated source voltages.

### 5 | CONCLUSION

The performance of a battery-supported UPQC small hydro turbine driven SCIG feeding non-linear and unbalanced loads has been studied in detail. The battery-supported UPQC is designed, modelled and simulated with small hydro-driven SCIG system in MATLAB environment. The battery-supported UPQC has given satisfactory performance with respect to improved voltage, frequency and power quality under different loading conditions. The battery-supported UPQC has also been found capable to maintain constant load terminal voltage even at reduced and above than rated source voltages. The performance of a battery-supported UPQC has also been studied on an experimental prototype in the laboratory. The battery-supported UPQC has also given satisfactory results with hardware implementation of an SCIG feeding unbalanced non-linear load.

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**APPENDIX**

Simulation parameters: Induction generator 3.7 kW, 230 V, 50 Hz, star connected.

\[ L_f = 5 \text{mH}, \quad R_f = 6 \Omega, \quad C_f = 4 \mu \text{F}, \quad \text{and} \quad C_{dc} = 1600 \mu \text{F}, \]

\[ V_{dc} = 700 \text{V}, \quad K_{ia} = 2.45, \quad K_{ps} = 0.198, \quad K_{pp} = 0.01 \quad \text{and} \quad K_{ip} = 2.54. \]

Turbine characteristics:

\[ T_{sh} = K_1 - K_2 \omega_m, \quad \text{where} \quad K_1 = -774.7 \quad \text{and} \quad K_2 = 4. \]

Experimental parameters:

230V, 3.7kW SCIG, 50Hz.