NEW HYBRID TOPOLOGY OF VOLTAGE REGULATION APPLIED IN THREE-PHASE FOUR-WIRE SYSTEMBASED ON INDUCTION GENERATOR

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Abstract **–This paper deals with the development of a new hybrid topology for voltage regulation in micro hydro power station using self-excited induction generator applied in three-phase four-wire systems. The proposed topology is a combination of a three-phase four legs static VAR compensator (SVC) and capacitor banks connected in parallel to the AC voltage bar. It is considered a three wires generator with no accessible neutral point being the neutral terminal for the load created through the neutral terminal of the excitation capacitor and the fourth leg of SVC, which provides the choice to connect the loads either star or delta configurations. A control algorithm and a project for the variable capacitors are proposed based on the specifications of the SVC. The proposed generating system is modeled and simulated in MATLAB. Simulation results and preliminary experimental results are presented to demonstrate the performance of the proposed new hybrid method for the voltage regulation of the self-excited induction generator. In the sequence, simulation results are presented in order to demonstrate the capability of theproposedsystem for feeding three-phase and single-phase balanced and unbalanced loads, with no distortion of the generated voltages.**

Keywords **-hybrid topology, micro hydro power station, three-phase four-wire systems.**

I. INTRODUCTION

The hydropower has been and must remain for many years the most important source of electricity in many places of the world, even with the rising interesting in nonconventional power sources, like wind, solar, biomass among others.

Micro Hydro Power generation (up to 100 kW) has become more relevant with the rising interesting in distributed generation, once in isolated areas it can represent the only alternative for local electricity generation. In these cases, the use of synchronous generator can represent a high cost compared to the entire system cost.

Along the last decades studies have showed alternatives with the use of asynchronous generator, or mostly called induction generator (IG), presenting economical [2] and technical [3] advantages when the question is generation in isolated area. However, the amplitude and frequency of the voltage generatedby the self-excited induction generator (SEIG) depends on the load applied [4] requiring regulation of these quantities.

The regulation of the voltage at the SEIG terminals is done by controlling the reactive power balance of the system, that is, the reactive power provided by the excitation capacitor and the reactive power required by the own generator and by the load applied [5], [6]. In [7] is presented a classification of schemes of voltage control, all applied to the control of reactive power balance. Among the topologies usually applied two have more relevance.

In [8] and [9] it is proposed the switching of passive elements in parallel in order to compensate de reactive power in discrete way. This method has the advantage of do not inject high frequency components at the system and present lower cost and efforts of control, but the control of voltage occurs at discrete level, impairing the perfect regulation.

In [3], [10], [11], [12] and [13] is proposed the control and regulation of voltages generated by a micro hydro power station based in the employment of a PWM inverter as static VAR compensator (SVC) connected in parallel with the voltage bus in order to compensate the reactive power required by the system through the injection of reactive currents into the connection bus. This method offers adequate voltage regulation, however it requires a PWM inverter of equal power of the maximum reactive load to be feed, what shall elevate the cost of the entire system.

In [14] these two methods were applied together in a hybrid system of voltage regulation. It was proposed the use of capacitor bank plus SVC in parallel with SEIG in a three-phase three-wire system. This hybrid system allows a more appropriated adjustment of voltage, compared with the solution that only uses capacitors. Moreover, the hybrid system reduces the cost of the solution which only uses the SVC, since the SVC, in this case, compensates only the reactive power do not compensated by the capacitors, so being required a lower power converter (SVC) to achieve the voltage regulation. The disadvantage of the proposed system is that it does not allow the connection of single-phase loads, what make it not suitable for application with most part of conventional loads in isolated areas.

In [15] and [16] are proposed two distinguished topologies of three-phase four-wire generation systems based on IG, both using only SVC for voltage regulation.

This paper proposes the expansion of the topology presented in [14] for a three-phase four-wire system, which allows the connection of three-phase or even single-phase loads, with the advantages of the hybrid topology. To accomplish that the capacitor bank is connected in star way plus a four legs SVC, both connected in parallel to AC voltage bar. The proposed control system is implemented digitally using a Digital Signal Processor (DSP). The block diagram of the proposed topology is presented in Fig. 1.

Simulation results are presented to demonstrate the performance of the generation system under three-phase balanced and single-phase unbalanced load connection.

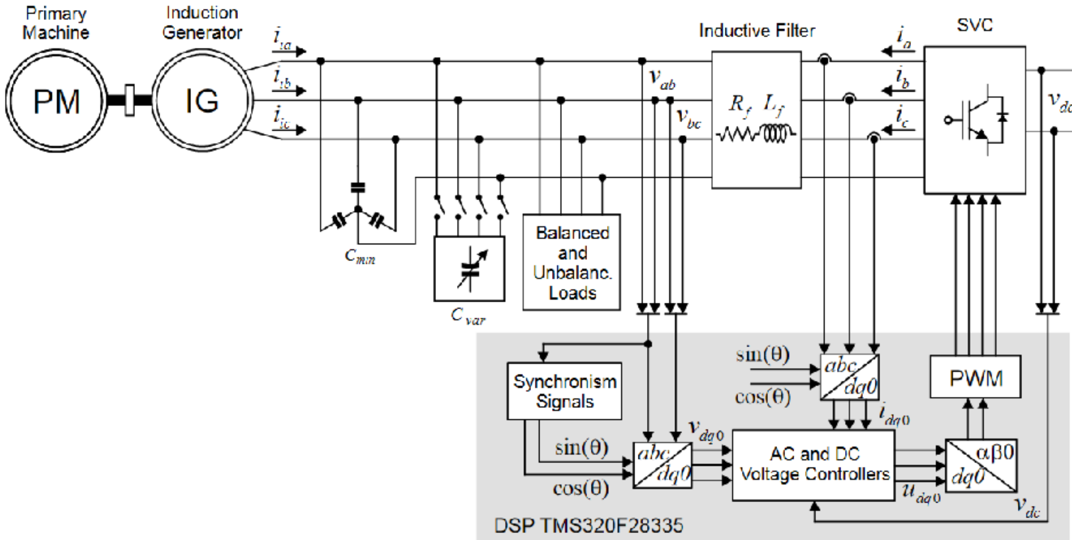

Fig.1. Block diagram of regulation system proposed.

II. DESCRIPTION OF THE SYSTEM

For the modeling of electric system composed by SEIG, self-excitation capacitor, output inductive filter and PWM inverter, shown in Fig. 1, the simplifying hypotheses are considered:

- The induction generator is considered an ideal voltage source, balanced and undisturbed.
- The DC bus capacitor of SVC is considered an ideal voltage source.
- The inductance of SVC output filter are identical and of equal value.
- The variable capacitors of regulation, Cvar, are disregarded.

Based on these hypotheses and applying the voltage and current Kirchhoff's law in the circuit of the Fig. 1, it is possible to represent by state space the system in dq0 rotation coordinate, according to the following equations:

$$\dot{\mathbf{x}}_{dq0}(t) = \mathbf{A}_{dq0}\mathbf{x}_{dq0}(t) + \mathbf{B}_{dq0}\mathbf{u}_{dq0}(t) + \mathbf{F}_{dq0}\mathbf{w}_{dq0}(t) \qquad (1)$$

where:

$$\mathbf{x}_{dq0} = \begin{bmatrix} i_d \\ i_q \\ i_0 \\ v_d \\ v_q \\ v_0 \end{bmatrix}; \quad \mathbf{u}_{dq0} = \begin{bmatrix} u_{d\_pwm} \\ u_{q\_pwm} \\ u_{0\_pwm} \end{bmatrix}; \quad \mathbf{w}_{dq0} = \begin{bmatrix} i_{id} \\ i_{iq} \\ i_{i0} \end{bmatrix};$$

$$\mathbf{B}_{dq0} = \frac{Z_{base}}{L_f}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1/4 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}; \quad \mathbf{F}_{dq0} = \frac{1}{CZ_{base}}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix};$$

$$\mathbf{A}_{dq0} = \begin{bmatrix} -\frac{R_f}{L_f} & -\omega & 0 & \frac{Z_{base}}{L_f} & 0 & 0 \\ \omega & -\frac{R_f}{L_f} & 0 & 0 & \frac{Z_{base}}{L_f} & 0 \\ 0 & 0 & -\frac{R_f}{L_f} & 0 & 0 & \frac{Z_{base}}{4L_f} \\ \frac{1}{CZ_{base}} & 0 & 0 & -\frac{1}{CR_C} & -\omega & 0 \\ 0 & \frac{1}{CZ_{base}} & 0 & \omega & -\frac{1}{CR_C} & 0 \\ 0 & 0 & \frac{1}{CZ_{base}} & 0 & 0 & -\frac{1}{CR_C} \end{bmatrix}$$

i_d, i_q, i_0 - SVC currents in $dq0$ coordinate.

v_d, v_q, v_0 - Capacitor voltages in $dq0$ coordinate.

u_{d_pwm}, u_{q_pwm}, u_{0_pwm} - SVC voltages in $dq0$ coordinate.

i_{id}, i_{iq}, i_{i0} - SEIG currents in $dq0$coordinate.

R_C - Damping capacitor.

L_f, R_f - Filter inductance and resistance, respectively.

$Z_{base} = V_{base}/I_{base}$ - Base impedance.

III. METHOD OF VOLTAGEREGULATION

For voltage regulation at induction generator terminals, the hybrid system is formed by self-excitation capacitor bank (Cmin), variable capacitor bank (Cvar) and SVC, as shown in Fig. 2.

According to the algorithm developed and presented in the flowchart of Fig. 3, after system initialization, it is calculated the reactive power injected by the SVC in the system by the measurement of line voltages and SVC currents.

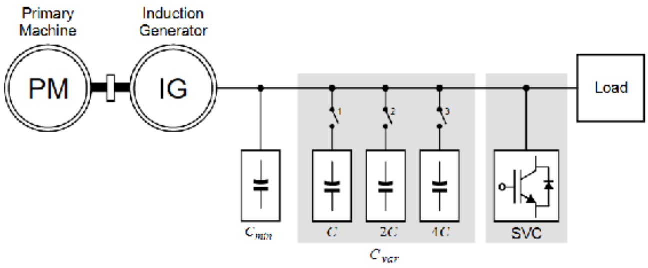

Fig.2.Hybrid system for voltage regulation.

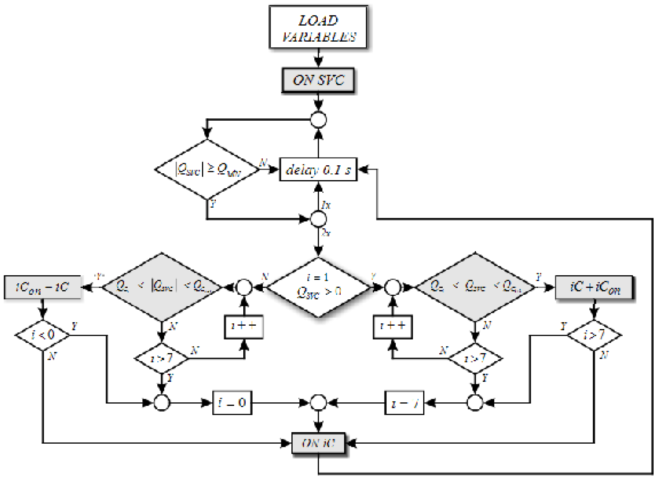

Fig. 3. Flowchart of the voltage control method.

According to Fig. 2, through the switches (1, 2, and 3) the capacitor banks are connected to the system performing the parallel connection between them. The parallel association of capacitor banks offers gradual reactive power compensation and consequently the system voltage regulation. The connection and disconnection of capacitor banks C, 2C, C+2C, 4C, C+4C, 2C+4C, or even C+2C+4C, happens in moments in which the reactive power of the SVC (QSVC) reaches a limit set, determined from the capacitor bank of lowest capacitance (C). Exceeding this limit, the algorithm tracks the bank that best fits the calculated reactive power and adds or subtracts the value found in the number of capacitor banks already connected.

A. Variable Capacitor Design

The operation of hybrid system is characterized by gradual connection of capacitor banks at the system. The connection of banks occurs in parallel with SEIG, in order to regulate the voltage at the established levels, where the capacitor project is based in the condition considering the connection of resistive loads at the system. The following equations are considered for the project:

$$Q_C = Q_{GV} - xQ_{Gen} \tag{2}$$

$$x = \left(\frac{V_R}{V_L}\right)^2 \tag{3}$$

$$Q_{GV} = \frac{{V_R}^2}{X_{CA}} \tag{4}$$

$$X_C = \frac{{V_R}^2}{Q_C} \tag{5}$$

$$C_{var} = \frac{1}{2\pi f X_C} \tag{6}$$

Where:

Q_C - reactive power to be compensated.
Q_{GV} - reactive power for excit. of IG at rated voltage.
Q_{Gen} - reactive power for excit. of IG at limit voltage.
x - constant of proportionality.
V_R - RMS rated voltage.
V_L - RMS limit voltage.
X_{CA} - capacitive reactance of excit. capacitors (C_{min}).
X_C - capacitive reactance for compensation.
C_{var} - capacitance of capacitor bank (C).

Q_{GV} and Q_{Gen} are obtained from the magnetization curve extract from the no load test of generator.

B. Static VAR Compensator

At the proposed method, the connection of the static VAR compensator, that is, the SVC, occurs for the fine adjustment of the voltage at adequate levels, since the capacitor banks just offer a voltage regulation in discrete way.

The design of proportional-integral (PI) controllers follows the proposed in [3]. The digital control system uses the synchronous dq0 coordinate system. Thus, the variables of the system should be transformed from abc to dq0 coordinates, which depends of proper synchronism signals (sine and cosine) as depicted in Fig. 1 and presented in [17].

Fig. 4 shows a simplified block diagram of the control system of the SVC in synchronous dq0 axis with two control loops being employed to control the SVC. The dc-link voltage is kept constant at a reference value by the control of d axis SVC current. Similarly, the control of ac voltages amplitudes generated by the IG is accomplished by controlling the reactive power flow, represented by q axis SVC current [10]. The third current control loop is applied to control the 0 axis SVC current and complement the signals needs for geometric modulation.

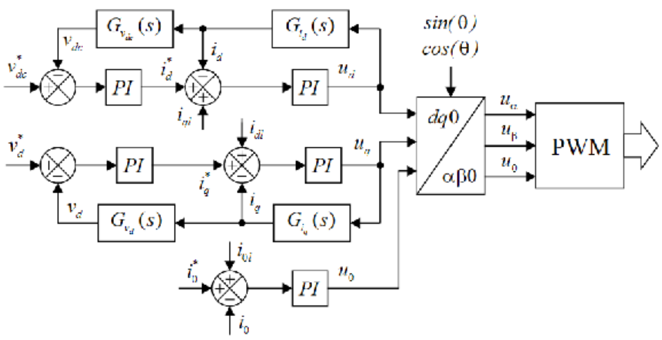

Fig. 4.Block diagram of the control system of the PWM inverter.

The SVC is able to compensate the unbalanced currents, caused by the connection of single-phase loads in AC bar, and this way, avoid unbalanced operation condition of the IG. This is another advantage of the proposed method once the IG is protected against unbalanced currents on its terminals, enhancing its time life. This is accomplished by the sum of normalized *dq0* load currents to the error signals processed by the PI controllers of inner control loops.

The transfer function (TF) $G_{id}, G_{iq}, G_{i0}, G_{Vcc}e\ G_{vd}$, required for the design of PI controllers applied to the inner loop of current and external loops of DC bus voltages of the SVC and output voltage of the generator, were obtained from the modeling presented in Section II. Considering the system parameters provided in Table II and using the First Order Holder method (FOH), the TF in the discrete domain are:

$$G_{i_d\_i_q}(z) = \frac{0.5997z^3 - 0.5985z^2 - 0.5992z + 0.598}{z^3 - 2.995z^2 - 2.991z + 0.9964} \quad (7)$$

$$G_{i_0}(z) = \frac{0.1499z^3 - 0.1494z^2 - 0.1496z + 0.1495}{z^3 - 2.995z^2 - 2.991z + 0.9964} \quad (8)$$

$$G_{v_{cc}}(z) = \frac{-0.01064z - 0.01064}{z-1} \quad (9)$$

$$G_{v_d}(z) = \frac{-4.564.10^{-7}z^2 - 1.79\text{x}10^{-6}z - 4.564\text{x}10^{-7}}{z^2 - 1.618z + 1} \quad (10)$$

IV. SIMULATION AND EXPERIMENTAL RESULTS

The generation system shown in Fig. 1 was simulated in Matlab®. Table I shows the parameters of the induction generator and capacitor bank, while Table II shows the parameters of the variable capacitor bank, PWM inverter, and output filters, considered for the development of the experimental prototype.

TABLE I
Parameters of Generator And Capacitor Banks

Parameters	Value
Generator power	5 HP
Line Voltage of SEIG	380 V_{rms}
‘Generator rated speed	1730 rpm
Frequency	60 Hz
Stator Resistance	0.66 Ω
Rotor Resistance	0.264 Ω
Leakage reactance of stator	0.935 Ω
Leakage reactance of rotor	0.935 Ω
Rotor inertia	0.034 kg.m²
Self-excitation capacitor bank - C_{min}	40 µF (each)

TABLE II
Parameters of Variable Capacitor and SVC

Parameters	Value
Variable capacitor banks - Cvar (C, 2C, 4C)	(6 µF, 12 µF, 24 µF)
Nominal Current rms	20 A
DC bus capacitor	4700 µF/900 V
Output Filter (Lf,Rf)	(2.5 mH, 0.03 Ω)
Switching Frequency	10 kHz

The prototype developed uses an induction generator of 5 HP (3.73 kW) to perform the experimental tests of the generating system shown in Fig. 1. To emulate the behavior of the hydraulic turbine, an induction motor of 7.5 HP was used coupled directly to the generator shaft, being controlled by a frequency converter.

For the test of inner control loops of the voltage controller it is imposed changes in $dq0$axis reference current (i_d^*, i_q^* and i_0^*). The expected response is presented in Fig. 5, with the $dq0$ axis currents generated by SVC following the reference currents imposed.

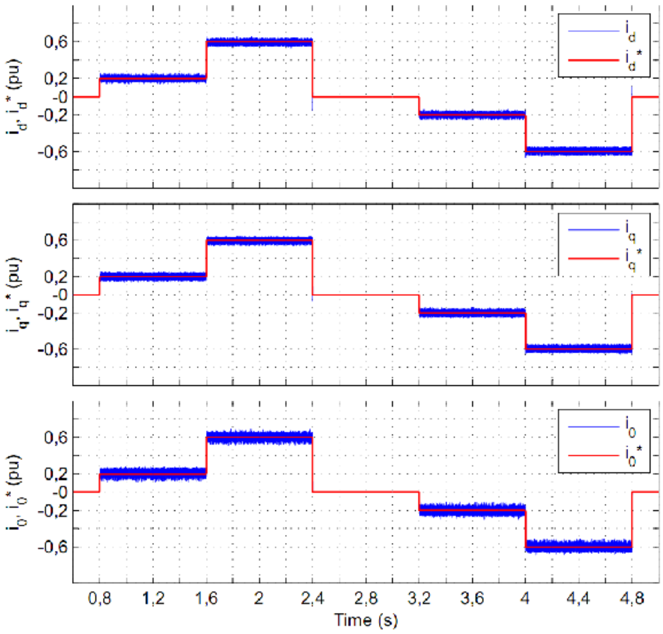

Fig. 5. Simulation results of the response of inner control loops of currents to changes in references i_d*, i_q* and i_0*.

The external control loop response of AC voltage is presented in Fig. 6, where the controller responds appropriately to changes in reference (v_d*).

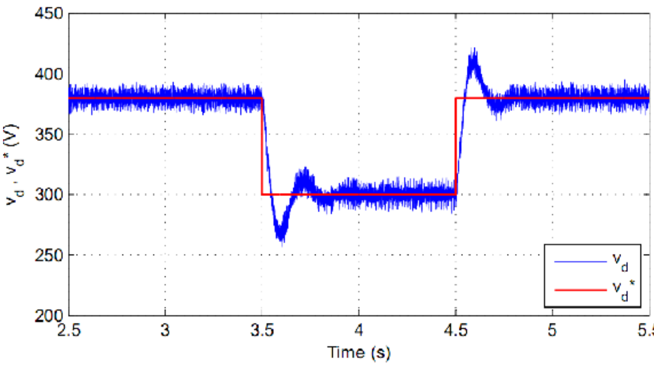

Fig. 6.Simulation results of the external control loop response of AC voltage to changes in reference v_d*.

In Fig. 7 it is presented the simulation results, showing the behavior of system variables, including line voltages, sequence of capacitor banks connection, SVC compensation currents and active and reactive power compensated by SVC, during three-phase balanced load connection and disconnection. Two three-phase resistive/inductive loads (1 kW resistive and 1 kVAr inductive) were connected at 3.5 s and 4.0 s and disconnected in the sequence, at 4.5 s and 5.0 s.

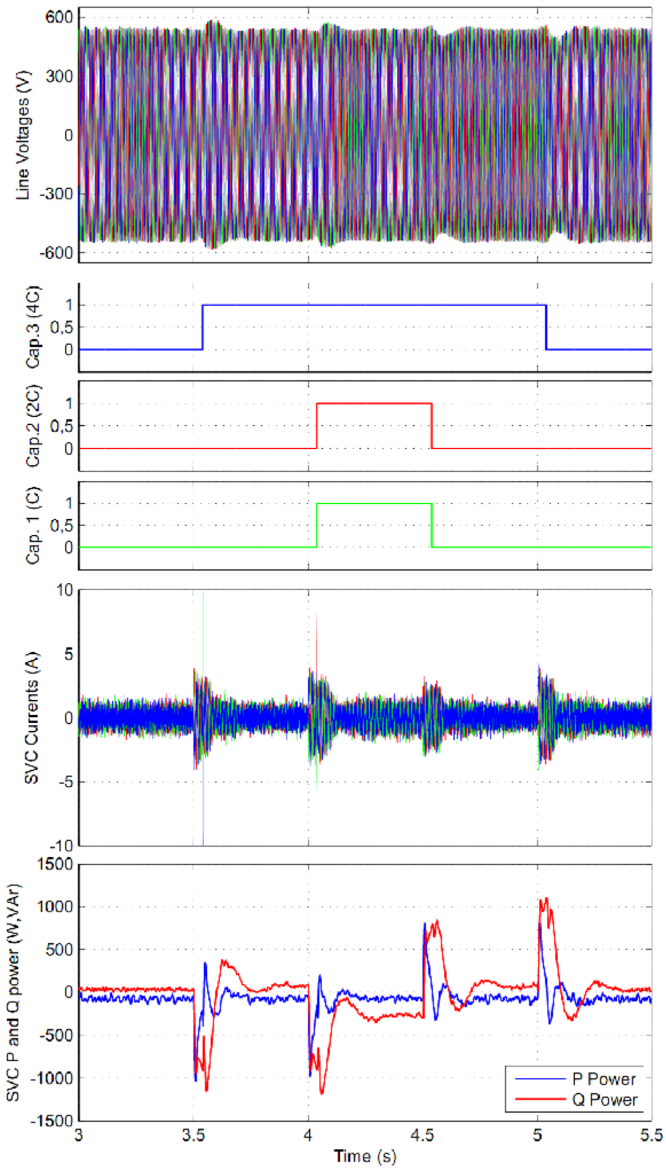

Fig. 7.Behavior of system variables during three-phase balanced load connection and disconnection.

In Fig. 8 it is shown in details the line voltages transitory during the connection and disconnection. Observe that system regulates the line voltages around 380 V_{rms} (537 V_{peak}) in about 0.1 s.

In Fig. 9 it is presented the behavior of the SVC without the connection of capacitor banks. It can be observed higher compensations currents and consequently higher reactive power compensated by the SVC.

One of the main objectives of the proposed method is to reduce the system costs by the reduction of the SVC rated power. Comparing Fig. 7 and Fig. 9, it is visible the effect of the capacitor banks on that. Observe that, capacitor banks compensate great part of the reactive power required by load and the power processed by the SVC do not cross over 1 kVA. So it can be concluded that, in this case, it could be applied a SVC with rated power limited to 1 kVA, what can be still improved with the reduction of the transitory peaks by the use of more advanced controllers.

In Fig. 11 it is presented the simulation result, showing the behavior of the system during single-phase unbalanced load connection and disconnection. Two single-phase resistive/inductive loads (1 kW resistive and 1 kVAr inductive) are connected in sequence, the first in phase *b* at 3,5 s and the second one in phase *a* at 4.0 s. In the sequence both loads are disconnected, the first in phase *a* at 4.5 s and the second one in phase *b* at 5.0 s. Observe that unbalanced currents are compensated by the SVC keeping the quality of generated voltages. Capacitor banks work by the same way compensating great part of reactive power required by loads.

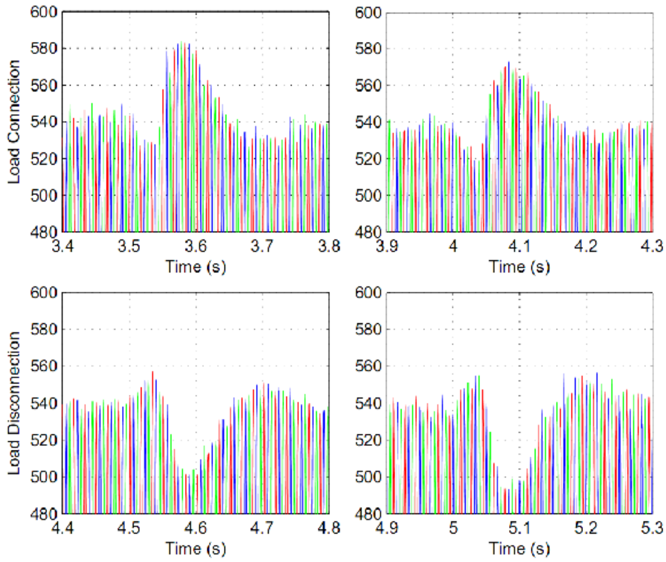

Fig. 8. Detail of line voltage transitory during load connection and disconnection.

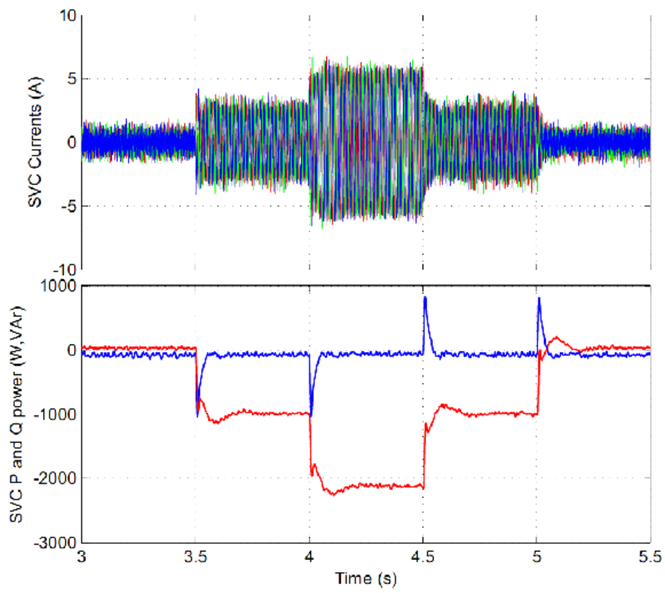

Fig. 9.SVC currents and power without the connection of capacitor banks.

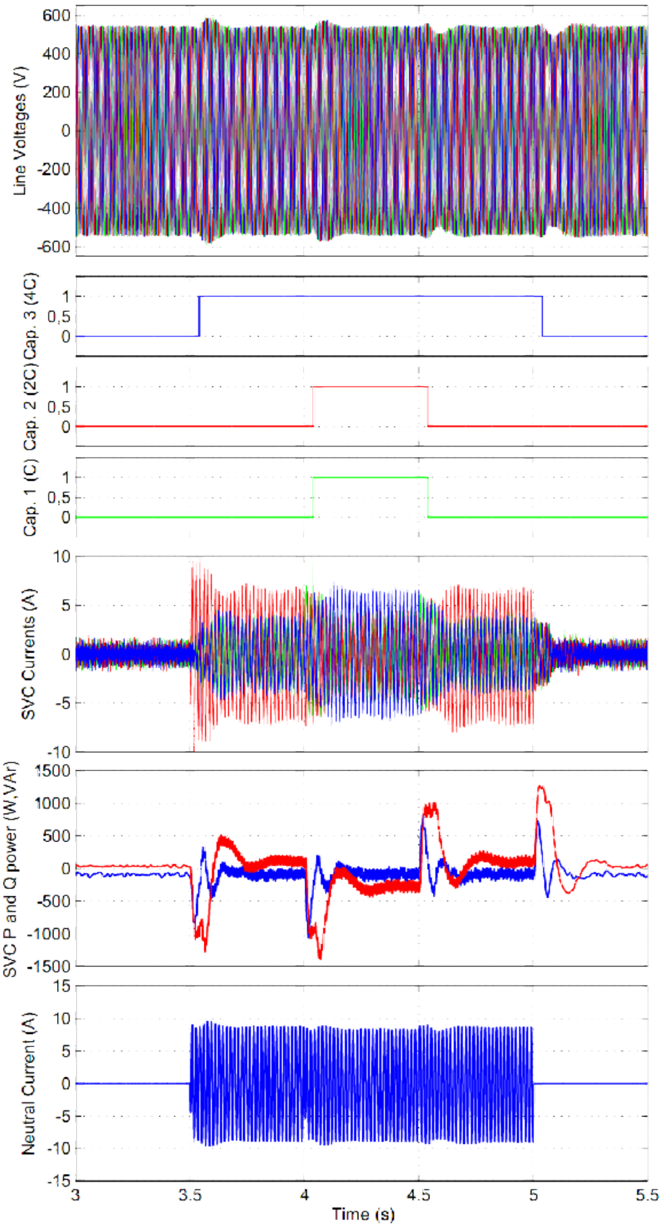

Fig. 10.Behavior of system variables during single-phase unbalanced load connection and disconnection.

V. CONCLUSION

This paper proposes the development of a new hybrid topology for voltage regulation of three-phase four wire micro hydro power station using SEIG. The proposed topology employs the connection of variable capacitor banks gradually in association with a PWM inverter. This method offers better voltage regulation compared to the method that uses only capacitors and overall cost reduction of the regulation system, compared to the method that uses only static VAR compensator, once it reduces the reactive power to be processed by the PWM inverter, so requiring a lower rated power PWM inverter. The simulation results considering the connection of three-phase balanced loads demonstrated the good performance of the proposed method in terms of voltage regulation and the reduction of power generated by the PWM inverter.Simulation results considering single-phase unbalanced loads proved the capacity of the system to deal with, offering balanced voltages to the loads and keeping balanced operation condition to the induction generator, what is desirable to increase its time life.

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