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Shunt Voltage Regulators for Autonomous Induction Generators, Part II: Circuits and Systems

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Abstract: - This paper presents different kinds of circuits used for autonomous induction generators output voltage regulation. Operation of SVC and STATCON based voltage regulators is explained, advantages and disadvantages of each type are shown. Different control strategies of voltage source and current source inverter based STATCONs are discussed. A novel current sensorless fixed frequency type of voltage regulator is also shown. In addition, extended simulation results are given, based on a real induction machine data

Key-Words: - Induction generators, voltage regulation, solid-state converters, current sensorless control

1 Introduction

Although the autonomous induction generator (AIG) has many advantages, like brushless construction, no DC supply for excitation, reduced maintenance cost, robustness and excellent transient characteristic, a capacitor-excited AIG suffers from inherent poor voltage regulation [1].

In most of the applications, a constant terminal voltage is required irrespective of the amount and nature of loads and speed. To regulate the voltage of an AIG with changing load and speed, the capacitors may be replaced or supplemented with an active external source of reactive power. The adjustment of speed is not easily possible and requires complicated control of prime mover. Load emulating is also possible, but it requires active power exchange between the regulator and the machine. Hence, the easiest way to maintain constant terminal voltage is to adjust the value of capacitance sees by the machine at its terminals [1-5].

When the regulator is connected in parallel with the load and the fixed capacitors bank, the configuration is called shunt voltage regulation, as shown in Fig. 1. This voltage regulating system must be able to create variable leading as well as lagging reactive power. The overall control scheme is common to all types of regulators: voltage magnitude is sensed, compared with a reference, processed by a controller, which combined with some reactive power generating waveform template outputs the command for the compensator switches, as shown in Fig.2.

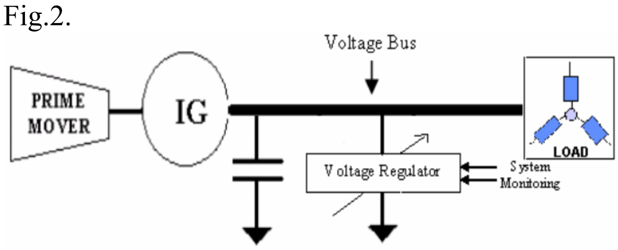

Fig. 1: A typical AIG system with shunt terminal voltage controller

This paper presents different types of shunt voltage regulators and is organized as follows: part 2 presents stepped-capacitor and saturable core reactor compensators, part 3 presents static VAR compensator (SVC) based voltage regulators, part 4 presents current- and voltage source inverter based STATCON voltage regulators, a novel current sensorless fixed-frequency voltage regulator is described in part 5, with some simulation results, which are given in part 6. The paper is concluded in part 7.

2 Simple Voltage Regulators

2.1 Stepped Capacitor Regulation

When a small variation in terminal voltage is permitted (around 6%), the regulator can be implemented by using few steps of capacitor and switched on/off manually or by relay/contactor

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arrangement. For example, for three-phase cage induction generator, three steps of capacitors in addition to the fixed capacitor bank can regulate the terminal voltage within 5% range [6]. The requirement of stepped capacitors to maintain the terminal voltage within some limit is reduced for higher rating of generator.

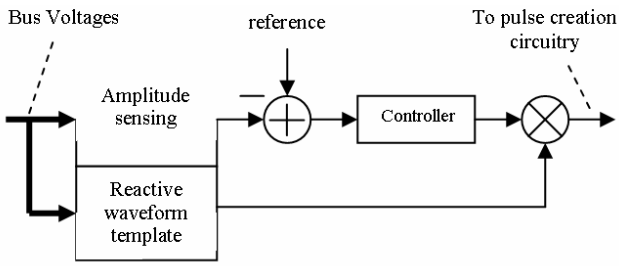

Fig. 2: Common control scheme of voltage regulation

2.2 Saturable Core Reactor Regulation

A shunt-connected saturable core reactor may be used as a variable static VAR generator [7]. The reactor functions as an auto excited magnetic amplifier. The value of fixed capacitor bank must be selected to provide the excitation to the machine and to feed the lagging reactive current required by the load even under the worst case of a pure inductive load. The reactor rating is decided so that it must absorb part of the reactive power under light or no load condition in order to maintain the desired voltage magnitude.

The disadvantage of both methods is the ability to perform only delivering reactive power (stepped capacitors) or absorbing it (saturable reactor), but not both. In addition, in the applications where variations in terminal voltage are not permitted, these methods are not suitable.

3 SVC-based Regulators

The SVC can be seen as a dynamic source of reactive current having sub-cycle reaction time. Using the thyristor valve as fast switches, capacitor banks can be switched in and out. Additionally, the thyristor valves can, by means of phase angle modulation, continuously control the current through an air core reactor. This combination of switching capacitors and controlling reactors provides continuous control of the reactive current output between two extremes dictated by component rating selection. SVC's utilizing phase angle control of reactors will produce current harmonics (of odd orders). The terminal voltage of an AIG can be maintained constant by thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) or by their combination [8].

The TCR is a linear reactor, connected in series with a thyristor valve made up of inverse-parallel, or "back-to-back" connected pairs of high-power, high voltage thyristors which are themselves connected in series to obtain the necessary total voltage and current rating for the valve [9]. A TCR design, using three single phase valves, connected in delta giving a six-pulse unit is shown in Fig. 3. The current is varied by controlling the gate firing instant of the thyristors and , hence, the duration of conducting in each half cycle, from 180^o firing angle delay as measured from applied voltage zero for minimum conduction, to 90^o delay for continuous conduction.

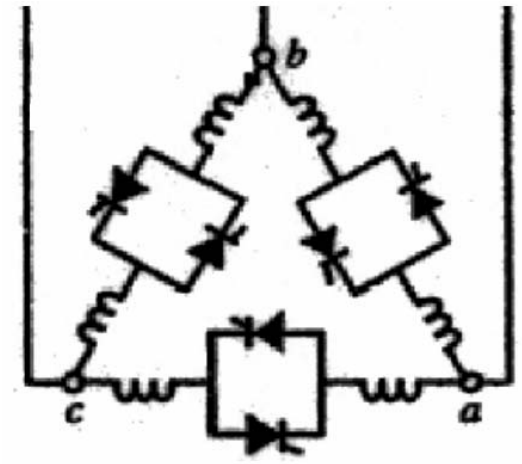

Fig. 3: Thyristor-controlled reactor circuit

TSC can give directly the effect of a variable capacitance, although the variation is not smooth, but in steps [9]. Thyristor valves consisting of inverse-parallel connected thyristors, generally similar to those used for the TCR, are used to give fast switching of three-phase delta connected block of capacitors, as shown in Fig. 4.

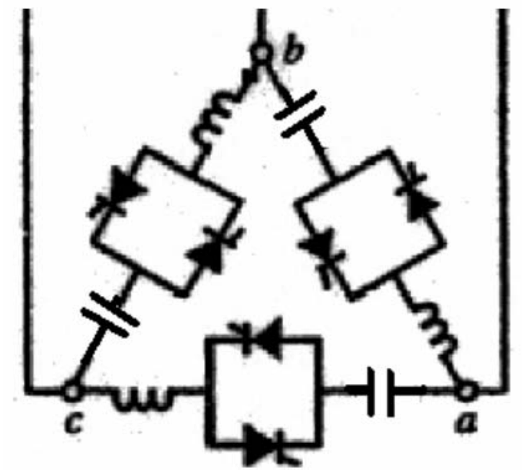

Fig. 4: Thyristor switched capacitor circuit

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TCRs are often used together with TSCs in order to give low power losses at zero VAR output. This configuration can also can also provide an increased operating range in the var generation region where frequent changes in output are required. In reference [10], a three-phase AIG excited by the SVC composed of the TCR in parallel with TSC and fixed capacitors bank was presented. The generated output voltage of the induction generator could be directly connected to non-sensitive to the AC frequency load facility installation and equipment such as heaters, battery chargers and energy storages. Inductive load changes and reference voltage variations were applied to build and test the SVC-based feedback control implementation system. Main drawbacks of such configurations are need for a bulky inductors and injecting low-harmonic current to the generator and the line.

3 STATCON-based Regulators

Most recent methods are mainly based on either voltage- or current- source static condensers (STATCONs). Such so-called solid-state synchronous voltage sources (SVS) are based on a DC/AC converter (or inverter), which is able to generate leading or lagging reactive power [11, 12]. Thus, inverters can be used as voltage regulators for AIGs. The power circuit of STATCON – based voltage regulator employs a three phase current controlled voltage [13-15, 17] or current source [16] inverter with an electrolytic capacitor or inductor in its DC bus, as shown in Figs. 5 and 6, respectively. However, the losses of a current-sourced converter tend to be higher than those of a voltage-sourced converter.

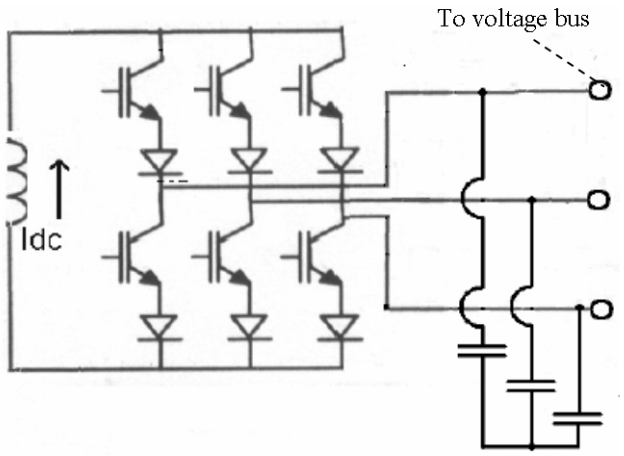


Fig. 5: Current-source inverter

A typical control scheme consists of two PI voltage controllers and one hysteresis current controller. One PI controller processes the difference between

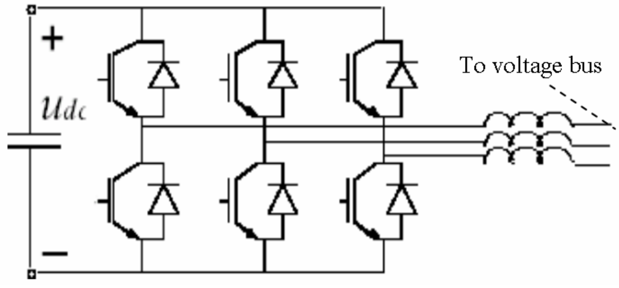


Fig. 6: Voltage-source inverter

the reference and actual bus voltage amplitudes, another one processes the difference between the reference and actual DC capacitor voltage, or DC inductor current. The output of the first controller is multiplied with quadrature reference currents template, which are computed to lead the corresponding AC voltages of the AIG system by 90^{o}. When the AC system voltage is less than the reference voltage, capacitive current flows from the STATCON to the AC system. When the AC voltage of the AIG is greater than the reference voltage, reactive currents flows from the STATCON to the AC system. The second PI controller controls the active power flow from the AC system to STATCON, needed to keep the average voltage of the DC bus capacitor or average current of the DC bus inductor at a constant value. The output of this controller is multiplied with in-phase reference currents templates, which are computed to be in phase with corresponding AC voltages of the AIG system. The sum of quadrature and in-phase of the above reference currents gives the reference STATCON currents. The hysteresis rule based controller controls the STATCON currents in a band around the desired reference current.

The voltage regulator provides the AIG with the desirable feature of a synchronous condenser, and is capable of operating in capacitive and inductive modes. The use of STATCON saves the AIG from de-excitation during the severe condition of load perturbation. It has a fast dynamic response for regulation the voltage when the AIG faces sudden load change. The voltage regulating scheme is adaptive to the changing load condition and hence it is possible to operate the AIG at almost constant voltage from no load to full load.

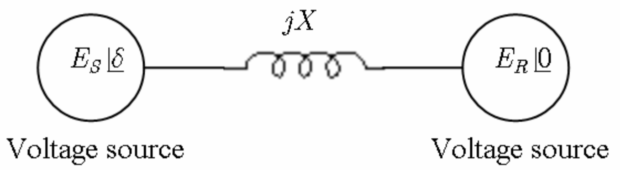
Another possible control scheme is based on reactive power theory [17]. However, DC bus and hysteresis current controllers remain the same, only the way of generating the reference currents are different.

The main drawbacks of the above mentioned configurations are:

- variable switching frequency because of hysteresis controller
- both currents and voltages need to be sampled

4 Current Sensorless Fixed Switching Frequency Regulator

STATCON-based voltage regulator, which overcomes the drawbacks, mentioned above, was proposed by the authors in [18]. The control system is based on the following principle. As it well known, transfer of power between sources, interconnected with a purely inductive reactance, as shown in Fig. 7, is as follows [19,20]: active power is directly proportional to the angle by which sending end voltage leads the receiving end voltage; reactive power transfer depends on voltage magnitudes, it is transmitted from the side with higher voltage magnitude to the side with lower voltage magnitude, as can be concluded from Fig. 7. Hence, by keeping the voltage source inverter output voltage in phase with the IG terminal voltage, we can control the reactive power transfer by changing the inverter output magnitude. In practice, a small angle between two voltages is necessary to compensate for the losses in the inductors because of the parasitic resistances and to maintain the inverter DC bus voltage or current at a desired constant value.



$$P = \frac{E_S E_R}{X}\sin\delta \qquad Q = \frac{E_S E_R\cos\delta - E_R{}^2}{X}$$

Fig. 7: Active and reactive power transfer between two sources

This configuration requires only terminal and DC capacitor voltage sensing, without any current sampling. In addition, the inverter is space vector modulated, therefore the switching frequency is constant.

5 Results and Discussion

In this section, some simulation results, based on the configuration described in the previous part, are presented. However, the voltage waveforms and voltage regulator outputs are common for all STATCON-based regulators, because they all follow the principles, described in [21, 22]. The AIG modelling equations are given in Appendix, machine data can be found in [21].

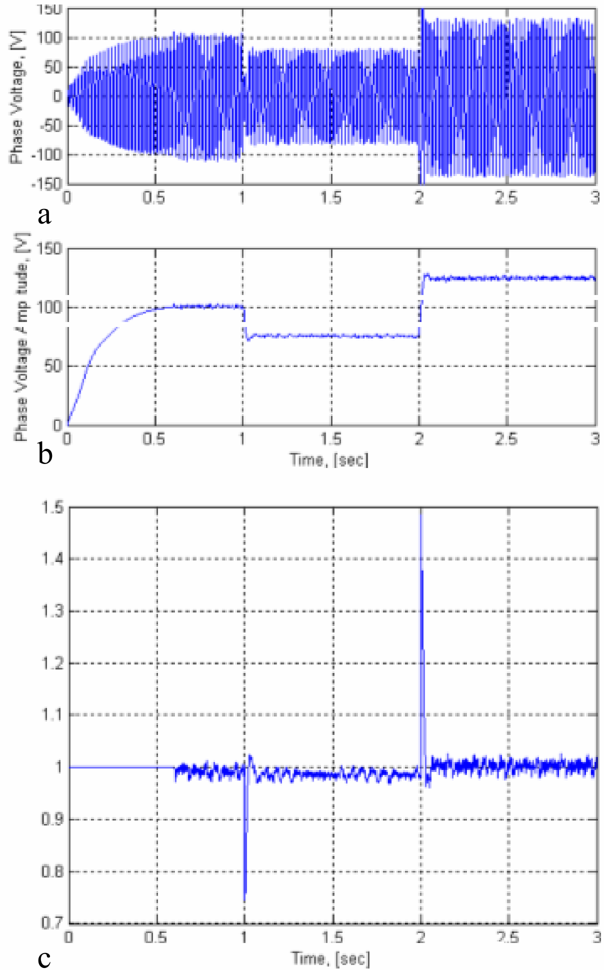


Fig. 8: System response to step change in reference voltage: a – phase voltage, b – phase voltage amplitude, c - inverter output voltage to terminal voltage ratio

System response to step change in reference voltage is shown in Fig. 8. The fixed capacitor bank is chose so that the terminal voltage at nominal speed no-load condition has the amplitude of 100V. The regulator is switched on at t=0.6s. Reference voltage is changed from 100V to 75V at t=1s and then to 125V at t=2s. It is clear that the regulation is fast and smooth. The regulator operates in inductive mode between 1s and 2s, absorbing reactive power and in capacitive mode from 2s, supplying reactive power.

Fig. 9 shows the result of simulation under the following conditions: speed = 0.9pu, at t=1.5s the IG is loaded with R=81 Ω. Because of the speed, the output voltage cannot build up to 100V amplitude. At the moment of regulator connection (t=0.6s) the IG receives the required amount of reactive power to increase the voltage amplitude to desired level. At the moment of load connection it is clear that the regulator current increases so that the voltage magnitude remains constant.

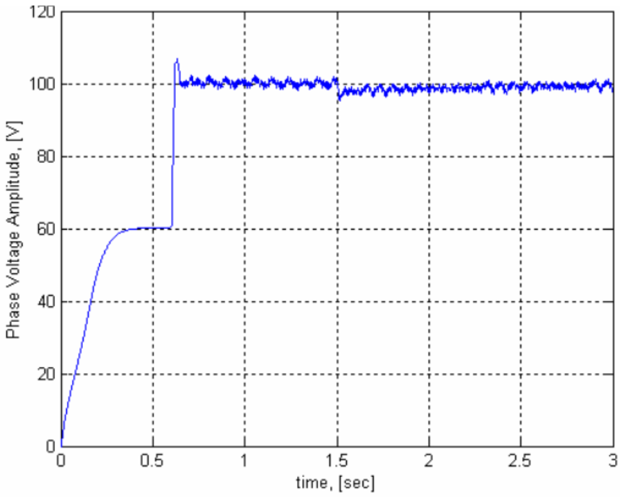


Fig. 9: Terminal phase voltage amplitude response to speed and load changes

6 Conclusion

Different kinds of circuits used for autonomous induction generators output voltage regulation were presented in the paper. Operation of SVC and STATCON based voltage regulators were explained, advantages and disadvantages of each type were described. Voltage and current source inverter based STATCONs were shown to be great candidates for modern AIG voltage regulation. A novel current sensorless fixed frequency type of voltage regulator was presented. In addition, extended simulation results were given, based on a real induction machine data

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Appendix: The induction machine, used in simulations, was modelled using the following equations [23]:

$$\frac{di_{sD}}{dt} = -\frac{1}{T_s'}i_{sD} + \frac{w_r k_r L_m}{L_s'}i_{sQ} + \frac{k_s}{T_r'}i_{rd} + \frac{w_r L_m}{L_s'}i_{rq} + \frac{u_{sD}}{L_s'}$$

$$\frac{di_{sQ}}{dt} = -\frac{w_r k_r L_m}{L_s'}i_{sD} - \frac{1}{T_s'}i_{sQ} - \frac{w_r L_m}{L_s'}i_{rd} + \frac{k_s}{T_r'}i_{rq} + \frac{u_{sQ}}{L_s'}$$

$$\frac{di_{rd}}{dt} = \frac{k_r}{T_s'}i_{sD} - \frac{w_r k_r L_s}{L_s'}i_{sQ} - \frac{1}{T_r'}i_{rd} + \frac{w_r L_r}{L_r'}i_{rq} + \frac{k_s u_{sD}}{L_r'}$$

$$\frac{di_{rq}}{dt} = \frac{w_r k_r L_s}{L_s'}i_{sD} + \frac{k_r}{T_s'}i_{sQ} + \frac{w_r L_r}{L_r'}i_{rd} - \frac{1}{T_r'}i_{rq} - \frac{k_s u_{sQ}}{L_r'}$$

$$k_s = \frac{L_m}{L_s}$$

$$L_s = L_{s1} + L_m \qquad k_r = \frac{L_m}{L_r}$$

$$L_r = L_{r1} + L_m$$

$$L_s' = \frac{L_s L_r - L_m^2}{L_r} \qquad T_s' = \frac{L_s'}{R_s}$$

$$L_r' = \frac{L_s L_r - L_m^2}{L_s} \qquad T_r' = \frac{L_r'}{R_r}$$

where

i_{sD}, i_{sD} - instantaneous values of direct- and quadrature- axis stator current components respectively and expressed in the stationary reference frame

i_{rD}, i_{rD} - instantaneous values of direct- and quadrature- axis rotor current components respectively and expressed in the stationary reference frame

L_s, L_{s1} - self- and leakage inductances of the stator respectively

L_r, L_{r1} - self- and leakage inductances of the rotor respectively

L_m - magnetizing inductance

T_s', T_r' - stator and rotor transient time constants respectively

u_{sD}, u_{sD} - instantaneous values of direct- and quadrature- axis stator voltage components respectively and expressed in the stationary reference frame

w_r - angular rotor speed