A Self-Excited Synchronous Generator for Small Hydro Applications

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Abstract: - With the increasing trend of distributed generation and the need for alternative and renewable energy sources, self-excited induction and synchronous reluctance generators have attracted more attention for wind, tidal and hydropower applications. This paper describes a class of self-excited synchronous reluctance generators (SRG) and presents preliminary test results obtained from an experimental machine. The concept of SRG described in this paper not only has the advantages of simplicity and ruggedness, but can also have enhanced steady-state characteristics and high efficiency over a wide range of operation. Additionally, its output frequency is determined only by the prime mover speed and this enables integration with power electronic devices to realise control schemes more economically. This proposed design provides a competitive alternative to both induction and conventional brushless synchronous generators used in stand-alone applications.

Key-Words: - Hydropower Plants, Self-Excited Generator, Small Hydro, Renewable Energy

1 Introduction

In the light of increasing electricity demand, international agreements to reduce greenhouse gases limiting the use of fossil energy, environment problems and the fact that in most European countries the sites for large hydropower are almost exploited, there is an increasing interest in developing small hydropower.

This trend has been enhanced by the EU Commission issuing the White Paper, 'Energy for the future: Renewable Sources of Energy' and the Directive 2001/77/EC, 'Promotion of Electricity Produced from Renewable Energy Sources', giving clear signals to increase the use of renewable energy in order to reduce environmental impact and create a sustainable energy system.

The White Paper calls for the use of 12 % energy from renewables and the Directive sets up specific goals to reach 22 % use of electricity from renewables in the EU by the year 2010. The Directive especially gives member countries a motive to consider small hydropower as it is the best proven of all renewable energy technologies. However, there are many barriers to overcome in order to increase the use of this natural source of energy. To strengthen its competitiveness, small hydropower has to become more economical [1], [4]. This paper focuses on a cost-effective design of a class of generators which has the potential of achieving efficient operation of small and micro hydropower plants.

1.1 Classification of hydropower plants

Water can be harnessed on a large or a small scale. The categories which are commonly used to define the power output form hydropower are outlined as follows [1,3]:

- Large-hydro: more than 100 MW and usually feeding into a large grid
- Medium-hydro: 15 - 100 MW and usually feeding a grid
- Small-hydro: 1 - 15 MW and usually feeding into a grid [2]
- Mini-hydro: between 100 kW and 1 MW; either stand alone schemes or more often feeding into the grid
- Micro-hydro: ranging from a few hundred watts for battery charging or food processing applications up to 100 kW, providing power for a small community or rural industry in remote areas away from the grid [1-5].

Until recently, it was believed that hydro was a green energy source as hydro-electric power plants do not emit any of the standard pollutants such as carbon dioxide and sulphur dioxide. Research has however shown that decaying vegetation that had been submerged by flooding produce greenhouse gases that are equivalent to other electricity sources, thereby contributing to global warming.

Micro and small hydro plants, on the other hand, have a minimal contribution to global warming. The primary design of a small hydro system is to divert some water, which is returned to the stream via the tailrace. Such systems also do not drastically affect river creatures. Fish and other animals still have access to the streams. Also, bacteria, which require stagnant water, are not common in small hydro systems.

Unlike large hydro plants, micro and small hydro do not require building of a dam. They convert the energy in flowing water to direct-drive shaft power or for electricity generation. The cost of the civil engineering work is therefore minimal. This, of course makes the generator cost a significant factor in the capital investment required. To this end, development of more robust and economical generators for small and micro-hydro applications would enhance the prospects of such schemes.

1.2 Power calculations

The theoretical power, P (W), available from a given head of water is directly proportion to the head, H (m), and the flow rate Q (m^3/s) as follows [3]:

$$P = kQH \qquad (1)$$

where the constant k is given as the product of the density of water and the acceleration due to gravity. The density of water is of course1000 kg/m^3 and the acceleration due to gravity is 9.8 m/s^2.

Turbines and generators are not perfectly efficient and the actual power available would be, about, 70% of that expressed in equation (1). For example, assuming a given head of 20 m, a flow 0.04 m^3/s, and a combined turbine-generator efficiency of 70%, the estimated output power would be 5.5 kW. This demonstrates how small the power available from a given site can be and, therefore, such an installation would need to as simple as possible; without compromising the reliability of the plant.

1.3 Generator topologies

Depending on the characteristics of the network supplied, a choice can be made between [5]:

- Synchronous generators equipped with a DC excitation system (rotating or static) associated with a voltage regulator, to provide voltage, frequency and phase angle control before the generator is connected to the grid and supply the reactive energy required by the power system when the generator is tied into the grid. Synchronous generators can run isolated from the grid and produce power since excitation is not grid dependent
- Asynchronous generators are simple squirrel-cage induction motors with no possibility of voltage regulation and running at a speed directly related to system frequency. They draw their excitation current from the grid, absorbing reactive energy by their own magnetism. Adding a bank of capacitors can compensate for the absorbed reactive energy. They cannot generate when disconnected from the grid because such generators are incapable of providing their own excitation current.

Synchronous generators are more expensive than asynchronous generators and are used in power systems where the output of the generator represents a substantial proportion of the power system load. Asynchronous generators are cheaper and are used in large grids where their output is an insignificant proportion of the power system load. Their efficiency is 2 to 4% lower than the efficiency of synchronous generators over the entire operating range.

In general, when the power exceeds 5000 kVA a synchronous generator would be favoured. In recent years, variable-speed constant-frequency systems (VSG), in which turbine speed is permitted to fluctuate widely, while the voltage and frequency are kept constant and undistorted, have entered the market [6]. The key to such a system is the use of a series- resonant converter in conjunction with a doubly-fed machine. Unfortunately the cost of theses schemes is still too high to justify their use in small hydro plants.

2 Synchronous Reluctance Generators

The self-excited generator topology considered here utilises an auxiliary stator winding in which an adjustable capacitor is connected. The stator also carries a distributed winding designed in such a way that higher-order harmonics can be reduced or even eliminated altogether. The proposed construction is illustrated schematically in Fig. 1.

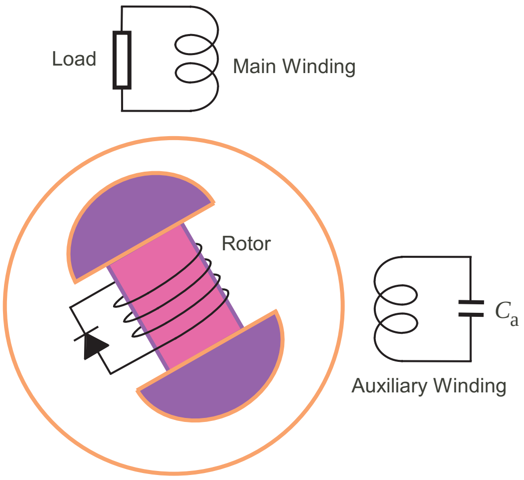

Fig. 1 Schematic diagram of SRG.

The auxiliary winding induces excitation voltage in the rotor field circuit. Tuning of the capacitor yields an effective way of achieving generator voltage regulation. The rotor laminations are stamped in such a way that significant reluctance effect is produced. This particular feature would have an effect on the dynamic operation of the generator.

The potential advantages of the proposed generator design are summarised as [7-9]:

- Self-excitation: no sliding contacts or a dedicated exciter, the structure is robust and simple.
- Voltage regulation via control of *stator excitation current* yielding improved waveform.
- Reluctance effect improves dynamic performance and stability.
- Output frequency is determined only by turbine speed enabling integration with power electronic devices to realise control schemes more economically.

3 Experimental Investigation

An experimental facility has been set up in order to verify the concept of the self-excitation and to identify design parameters that have most effect on its performance and control.

The experimental machine selected for this investigation is a standard six-winding ac machine (normally operating as a three-phase slip-ring induction motor). With the aid of two diodes, the rotor phases are connected to yield a *fixed-axis* excitation, as shown in Fig. 2 (a). The stator phases are connected as shown in Fig. 2 (b) to yield a magnetically equivalent system having two windings with a 90^o in space displacement. Thus, one of the three phase stator windings is shunted by a capacitor, and it represents the auxiliary winding of Fig. 1, while the other two phases are connected in series to yield the load winding. The machine has a cylindrical rotor. Therefore it was not possible to simulate or investigate the reluctance effect depicted in the construction of Fig.1.

3.1 Description of the test-rig

A separately-excited dc motor was mechanically coupled to the experimental machine. The dc machine acts as the prime mover, driving the generator at a synchronous speed ω_s. As shown in Fig. 3, the armature of the dc motor was fed from a three-phase thyristor rectifier while the field winding was energized from a single-phase diode rectifier. This arrangement enables speed adjustment.

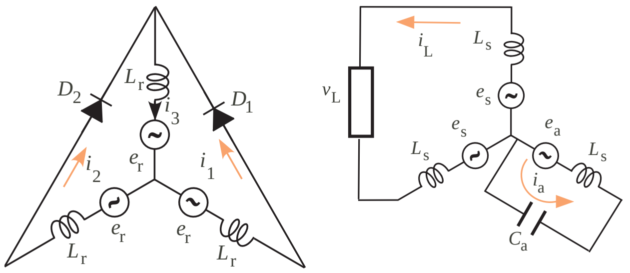

Fig. 2. Connections of self-exited single-phase synchronous generator: a) rotor and b) stator.

3.2 Operation

The prime mover (dc machine) is started-up and its speed is adjusted to the synchronous value. As soon as the generator starts rotation, the residual flux in the rotor induces a small voltage in the stator winding (referred to here as the residual voltage). This residual voltage results in a current to flow in the stator-auxiliary winding which is short-circuited by a capacitor. The auxiliary winding (capacitance) current sets up a pulsating magnetic field in the air-gap which can be resolved into two components both rotating at the synchronous speed; one rotating in the same direction as the rotor (forward) and the other rotates in the opposite direction (backward). The backward flux component induces a double-frequency voltage in the rotor winding, which, with the aid of the diodes, results in unidirectional field currents. This field current, with rotor rotation, causes the voltage induced in the stator auxiliary winding, its current and air-gap flux to increase. This increases the induced rotor voltage and the field current. This cumulative action continues for a few cycles until the steady-state condition is achieved.

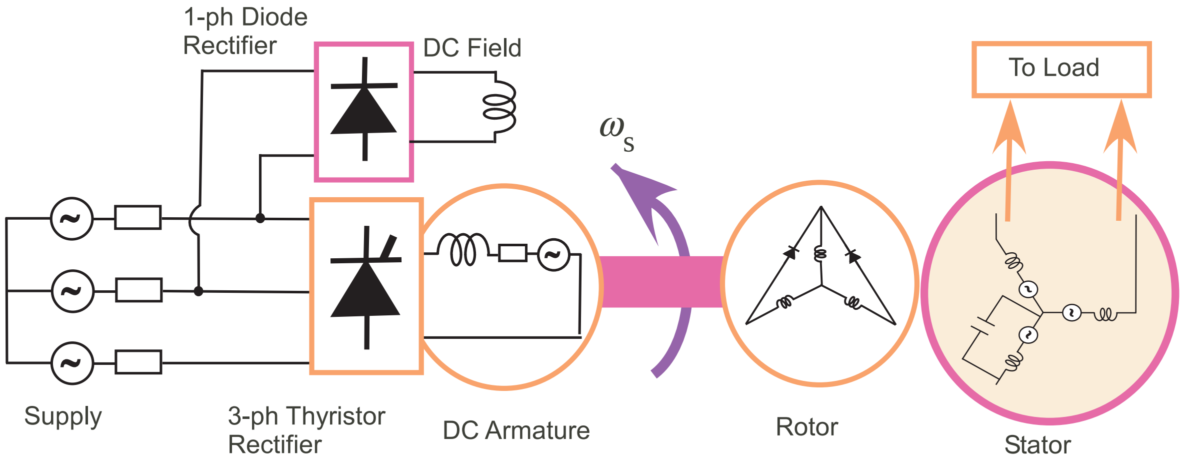

Figure 3: Schematic description of the test-rig

4 Results

The value of the auxiliary winding capacitance not only has a profound effect on the generator's steady-state operating conditions; it also determines whether or not self-excitation can be achieved. Determination of the critical capacitance value is beyond the scope of this paper.

Figs. 4 and 5 show the output voltage, at no-load, and excitation current waveforms during the process of establishing self-excitation. It is seen that it takes approximately two cycles of the fundamental frequency for the output voltage to reach the steady state value (Fig. 4). Similarly, the field (diodes) current reaches the steady state in two cycles, as illustrated in Fig. 5.

Fig. 4 shows that the generated voltage contains higher-order harmonics. The waveform must be improved for the design to be of a practical value. This can be achieved by suitably designing both the auxiliary (capacitance) and load (main) winding.

The load characteristics (voltage versus current) were determined by connecting a variable resistance across the main winding terminals of the experimental machine. The rms values of load current and voltage were recorded as the load (resistance) was varied. The results are given in Fig. 6. It is noted that as the load current increases, the load voltage decreases (at no load voltage is 286 V it drops to 252 V when the machine is delivering 8 A, i.e. voltage regulation of about 12%). This is because the voltage drop across the machines internal impedance increases with load. This is yet another issue that needs to be addressed when designing a prototype machine. The load voltage can be kept within allowable limits by adjusting the value of the capacitance used in the auxiliary winding.

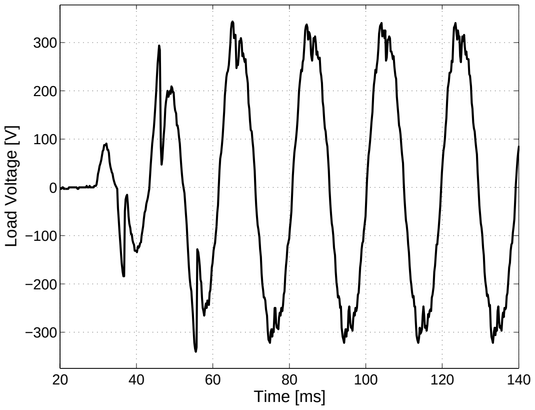

Figure 4: Self-Excitation of load voltage.

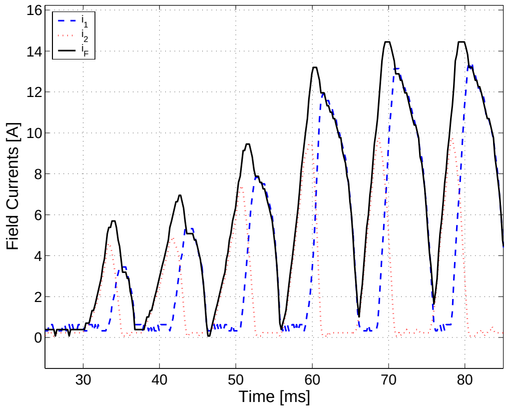

Fig. 5: Self-Excitation field currents.

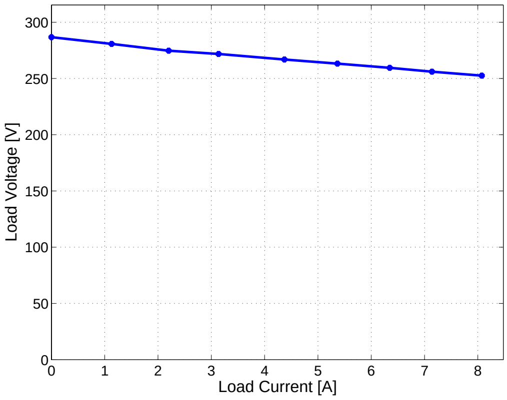

Fig. 6: Load characteristics of self-excited generator.

5 Conclusion

The paper identifies small- and micro-hydro power generation as possible means of increasing the use of renewable energy in order to reduce environmental impact and create a sustainable energy system. It proposes a suitable generator topology for such applications, offering the advantages of ruggedness, simplicity and ease of control.

The experimental work described in this paper identifies critical design issues that must be addressed for the presented generator topology to achieve wide acceptance. The two main issues relate to the distortion of the generated voltage (due to generated harmonics) and the excessive voltage regulation. The first drawback can be overcome by tailoring the winding design while voltage regulation can be improved by adopting a suitable control scheme. These design issues are currently being investigated and it is hoped to report on progress made in the near future.

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