VOLTAGE AND FREQUENCY CONTROL FOR ISLAND OPERATED INDUCTION GENERATORS

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ABSTRACT

Over the last few years the interest in distributed generation and island operation of small production units has increased. Many of the existing such units are hydro power stations with induction generators. These are not initially constructed for island operation, but with some extra equipment this kind of operation is feasible. In this paper the behaviour of two parallel-operated induction generators driven by hydro turbines are studied during load steps. The influence of a STATCOM based voltage regulator is also investigated and it is shown that a fast voltage regulator may not be desirable for induction generators in combination with hydro turbines.

INTRODUCTION

The fact that it is possible to operate an induction generator excited by fixed capacitors in island operation has been reported in several papers. It has also been shown that voltage control could be obtained by installing a variable reactive power source, e.g. a STATCOM [1]. Island operation with induction generators has been studied earlier in combination with small hydro power plants [2]. While that paper used dump load for frequency control, this paper uses a turbine governor.

This paper demonstrates parallel operation of two 2 kW induction generators, with controllable turbine power and STATCOM. The results are based on simulations and laboratory experiments.

ISLAND OPERATION

To perform black start on an induction generator, fixed capacitors are connected to the generator terminals.

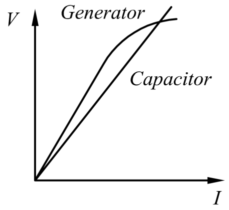

Fig. 1. Induction generator magnetizing curve and capacitor characteristic.

When the generator is accelerated the remanence in the generator excites the LC circuit, formed by the generator and the capacitors. The voltage rises to the point where the nonlinear generator and linear capacitor curves in Fig. 1 intersect and a stable operating point is obtained. If the capacitors are selected for no-load compensation of the generator, the resulting terminal voltage is close to nominal voltage. When the generator is loaded and the current increases, the required reactive power to the generator is increased. To be able to maintain the nominal voltage when the load increases more reactive power is needed. Instead of connecting more capacitors the reactive power can be supplied, and continuously controlled, by a STATCOM. The STATCOM reactive power output could be controlled to be either positive or negative. No load reactive power is thus produced by fixed capacitors and the additional reactive power is supplied from the STATCOM.

Test System

The simulation model is adapted to available laboratory equipment. To study parallel operation of induction generators a model with two 2 kW generators with hydro turbine and STATCOM is used, Fig. 2. A nonlinear model assuming inelastic water column is used for the hydro turbine and waterways [3]. The water starting time is set to 2 s. In the laboratory a converter controlled DC motor is controlled to behave like the turbine and waterways. Each unit has an inertia constant of H=0.15 s.

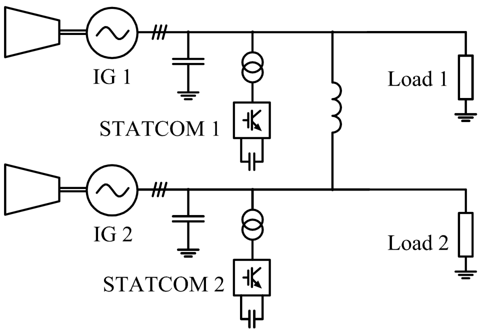

Fig. 2. Simulation and laboratory model with two parallel induction generators driven by hydro turbines.

The fixed capacitors are selected for nominal generator voltage at no load and are selected based on the generator parameters according to [5]. The resulting 117 μF corresponds to a generated reactive power of 1780 var. A 1.5 kvar STATCOM is connected in parallel with the fixed capacitors at each generator. The two generator bus bars are connected together through a 3 mH inductance. Parameters for the generators are listed in Appendix I.

Frequency Control

A turbine governor designed for a large power plant connected to a strong grid is generally equipped with a permanent droop function. This function introduces a permanent control error proportional to the output power, i.e. the gate opening, and allows parallel operating generators to share the load equally.

In island operation a large load step may result in a large output signal from the regulator and this leads to overshoot in gate opening and frequency and may lead to instability. Therefore an additional droop function is introduced in the control loop, Fig. 3. This transient droop function reduces the step response and improves the stability of the island-operated system [3].

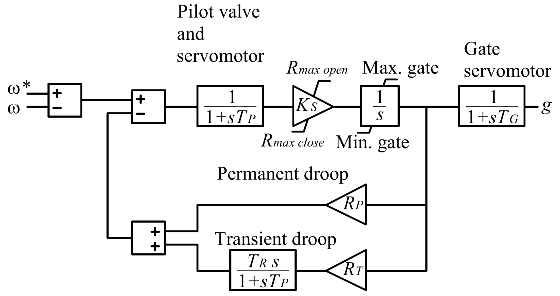

Fig. 3. Turbine governor with permanent and transient droop functions.

$R_{max\ open}$ and $R_{max\ close}$ represent the maximum gate opening and closing speed, in pu/s, while *Min gate* and *Max gate* indicate the end positions of the gate. The output from the integrator, i.e. the servo motor position, is fed back to the droop functions. This kind of governor is described in [3] and [4].

Voltage Control

In an island system with induction generators the voltage is strongly dependent on the speed of the machine and the other way around. This means that a fast acting voltage regulator lowers the frequency even more after a load step. It is therefore natural to include a transient droop function in the voltage regulator in Fig. 4, just like the one in the turbine governor above. The fast step response is then suppressed by the transient droop function, which facilitates both voltage and frequency control.

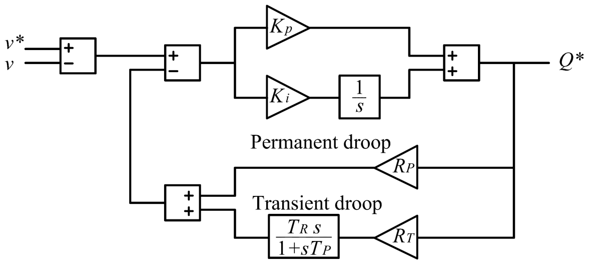

Fig. 4. STATCOM voltage regulator with transient droop compensation.

Parameters for turbine governor and voltage regulator are listed in the table below.

TABLE I
REGULATOR PARAMETERS

Turbine Governor		Voltage regulator	
T_P	0.2 s	K_P	1
K_S	5	K_i	0.5
T_G	0.2 s	R_P	0.04
R_P	0.04	R_T	0.9
R_T	7	T_R	12 s
T_R	2s		
$R_{max\ open} = R_{max\ close}$	1/30 pu/s		

TEST SYSTEM PERFORMANCE

To determine if it is possible to operate hydropower induction generators in parallel the system in Fig. 2 is simulated in MATLAB SIMPOWERSYSTEMS and tested in the laboratory. Another important issue is if it is possible to maintain acceptable voltage and frequency values during load steps.

Black start is performed on each generator individually by accelerating the generators with the fixed capacitors connected. Once the voltage is raised the STATCOM is started and the stations are synchronized.

Dynamic Properties of Load Changes

In Fig. 5 the generators run at 25% of rated power, when an additional load of 4% with tanφ=0.2 is connected. The transient voltage and frequency droops act to reduce the step response for both active and reactive power. At about 20 s after the step, the values are close to their nominal values again. In Fig. 5 both simulation and laboratory results are presented. Due to losses in the DC motor and the generator the gate opening at no load is about 0.2 pu (400 W). This is a drawback with using small laboratory machines where the losses are relatively higher than for big

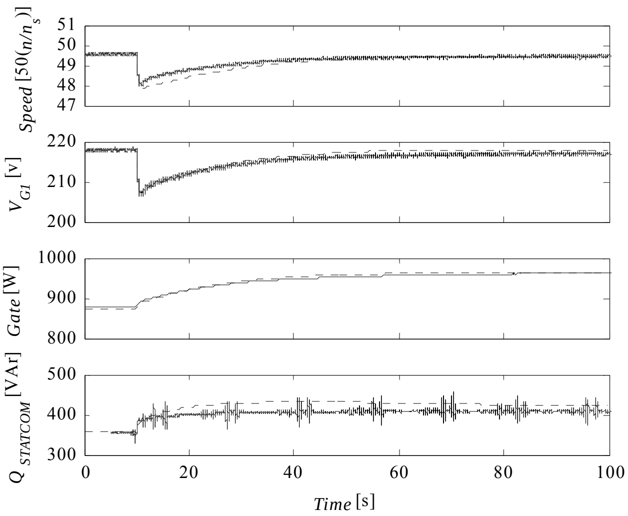

Fig. 5. Increasing load from 25% (1000 VA) to 29% (1160 VA) from simulation (dashed) and laboratory (solid). From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.

machines. The deviation between the simulations and laboratory results in Fig. 5 is probably caused by differences in generator parameters. The slope of the magnetizing curve also has a great impact of the result.

The two turbine governors are set to share the load equally and hence the measurements from station 2 are identical to those from station 1 presented in Fig. 5. The behaviour when disconnecting load is the same but with the curves in Fig. 5 inverted.

The case with constant power load is investigated in the laboratory. In this experiment only one STATCOM is controlling the voltage at the two parallel generators. The other converter is used as a controllable constant power load. In Fig. 6 the generators are operating at no load when 6% constant active power load is connected at 10 s and 6% constant reactive load at 75 s.

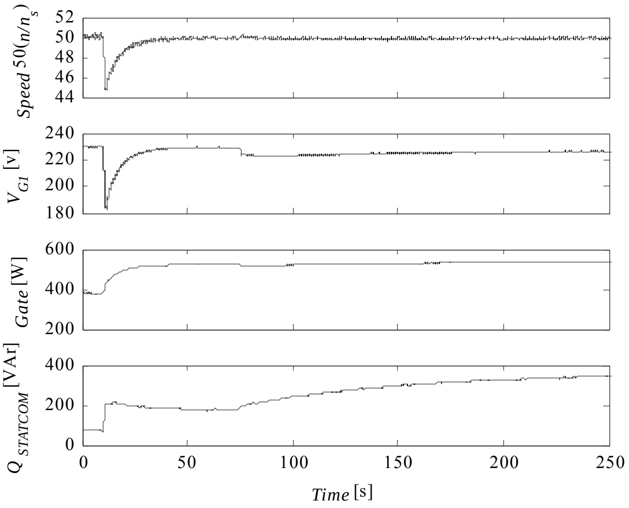

Fig. 6. No load operation, connecting 6% constant active power load (250 W) at 10 s and 6% constant reactive power (250 var) at 75 s. Laboratory measurements, from top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.

When connecting active power load the gate opening is increased to maintain nominal frequency but at the same time the required reactive power to the generator is increased and the STATCOM reactive power is therefore also increased. The reactive load has a slight influence on active power but mainly on reactive power.

Maximum Load Step

To decide if island operation is feasible it is important to determine the maximum load step that is possible while maintaining acceptable voltage and frequency values. To do this the lowest and highest permitted frequency values have to be defined. In a power system the problem with frequency deviations is mainly connected to induction motor loads. At low frequency the motors are heated and in the worst case they may stall. Therefore the standard for induction machines, IEC 60034-1 [6], is studied. Both motors and generators are discussed in the standard but due to the fact that many of the small induction generators are originally constructed as motors, this is the only case considered. Based on this standard and on the Svenska Kraftnät TSO requirements on production units [7], the acceptable frequency is set to 47.5 – 52.5 Hz. These limits are used when maximum load steps for the generators are determined. As shown in Fig. 7 the generators are capable of handling bigger load steps when already loaded and the relation is linear in the considered range. Due to the high losses in the laboratory machines readings above 0.5 pu are not reliable and are therefore excluded.

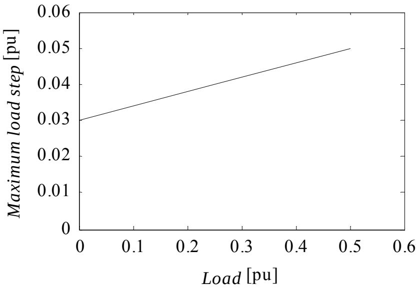

Fig. 7. Maximum load step as function of loading before the step, if frequency must be kept in the interval 47.5-52.5 Hz.

The results above are based on a limited frequency range. However it may be of great interest to assess the behaviour at larger load steps for example when the generator is black started. Therefore the lowest voltage and frequency, obtained after an increase in load, is determined as function of the size of the load step. In Fig. 8 different load steps are applied when the generators are running at no load. At lower load steps the lowest voltage and frequency is almost proportional to the step size. Both voltage and frequency reach low values when big load steps are applied but most importantly the system is still stable.

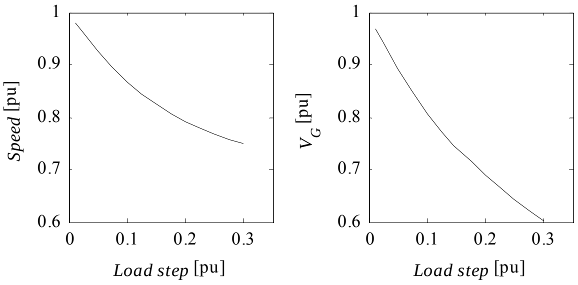

Fig. 8. Lowest frequency (left) and voltage (right) after a resistive load step as function of the step in per unit of the total generator capacity.

Influence of Turbine Governor

Provided that the acceptable frequency deviation is ±2.5 Hz, the largest load step is determined with different gate opening rates. The simulations show that with a gate opening time of less than 60 s the time has no influence on the maximum step. This means that a standard turbine servo could handle this without any problem. However it does not mean that a fast servo is unnecessary in all situations. If a fault occurs and the generator is disconnected from the grid it is important to be able to stop the turbine as fast as possible. The result is obtained with an inertia constant of H=0.15 s and may differ from a unit with a different inertia constant.

Influence of Voltage Regulator

To illustrate the importance of a slow voltage regulator, simulations are performed with a slow and a fast voltage regulator, i.e. with and without transient droop compensation. The results are presented in Fig. 9 where two induction generators run in parallel and the load is increased from 25% to 29%.

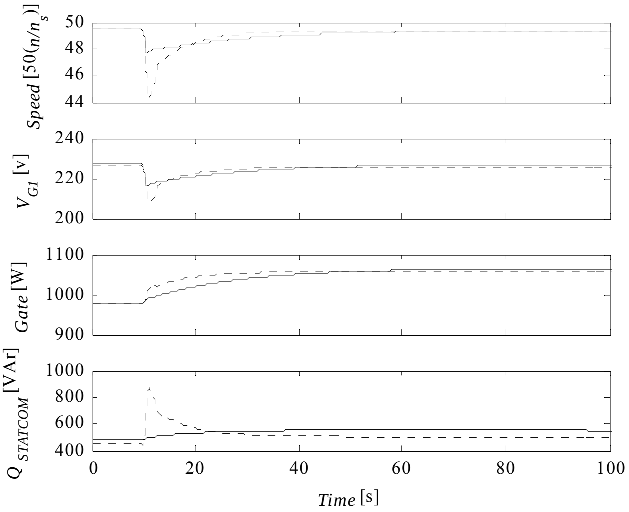

Fig. 9. Increasing load from 25% (1000 VA) to 29% (1160 VA). From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power. Fast (dashed) and slow (solid) voltage regulator.

As can be seen in the figure a fast voltage regulator is devastating not only to frequency but also to the voltage. Due to the big reactive power, the generator speed decreases more and the low speed results in a further decreased voltage. Then the STATCOM increases its reactive power even more and so on. This means that it is better to have a slow STATCOM that allows the frequency to stabilize before the voltage is adjusted back to its nominal value.

CONCLUSIONS

Two self-excited induction generators have been successfully operated in parallel in the laboratory and in simulations. The generators were driven by hydro turbines and were equipped with fixed capacitors and STATCOM for voltage regulation. When connecting and disconnecting impedance load and constant power load the system was found to be stable at least up to a load step of 0.3 pu.

Further it was shown that a slow voltage regulator facilitates both voltage and frequency control after a load step.

If it is required to keep the frequency in a fixed range the maximum load step is increased when the generators are loaded before the load step is applied. This means that stability is improved if the generators are already loaded when applying a load step. The relation between maximum load step and loading is linear.

The relation between the lowest frequency/voltage after a load step and the amount of power connected was investigated. Connecting larger load steps give lower voltage and frequency and the relation is almost linear for moderate step sizes. Even though the voltage and frequency reaches low values the most important thing is that the system is still stable.

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APPENDIX I

Generator parameters:
P = 2kW
V = 220V
R_s = 1.2Ω
R_r = 1.0Ω
$X_s = X_r$ = 2.4Ω
X_m = 35Ω