LOAD SHARING REALIZATION OF PARALLEL OPERATED SYNCHRONOUS GENERATORS WITHIN SHIP MICRO-GRID USING MICROCONTROLLERS

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ABSTRACT: This paper is focusing on parallel operation of synchronous generators, while explaining and presenting different applied methods of parallel operation and control of active and reactive load sharing between generators. Typical parallel operating distributed generators (DG) within a micro-grid system of a specific class of ships is discussed. The paper presents an advanced microcontroller based droop method of both active and reactive load sharing, suitable for ship's micro-grid system. A proposal of two rotary frequency converters (RFCs) setup has been introduced and studied through this paper. Equations describing the proposed set have been derived and overall model has been developed for simulation analysis using Simulink/Matlab software program. Experimental setup has been practically implemented and tested for two modes of operation; open loop and closed loop. By introducing closed loop microcontroller based feedback circuits for both voltage and speed droop compensation, parallel operation of the two rotary frequency converters has been achieved with load sharing capability. Hence, forming a simple and reliable multi-generator sets (micro-grid) suitable for ship equipments of different voltage and frequency load requirements.

Keyword: Digital controller, rotary frequency converters, speed and voltage droops, synchronization

List of Symbols:

- $V_m$ = Terminal voltage of induction motor.
- $V_t$ = Terminal voltage of synchronous generator.
- $V_f$ = Synchronous generator field voltage.
- $T_m$ = Motor developed torque.
- $T_g$ = Mechanical torque of the generator.
- $P_q$ = Active output power of the generator.
- $Q_g$ = Reactive output power of the generator.
- $P_l$ = Active power of the load.
- $Q_l$ = Reactive power of the load.
- $\omega_{sm}$ = Induction motor synchronous speed.
- $\omega_{sg}$ = Generator synchronous speed.
- $\theta_s$ = Angle of synchronous impedance $Z_s$.
- $\delta$ = Angle between $V_t$ and $V_f$.
- $\theta_l$ = Angle of load impedance $Z_l$.
- $f_g$ = Generator output frequency.
- $\Phi_g$ = Flux per pole due to the excitation current.
- $p_g$ = Number of poles of synchronous generator.
- $p_m$ = Number of poles of induction motor.
- $J$ = Mechanical coupling moment of inertia.
(I) INTRODUCTION:

In today’s world, an isolated generator supplying its own load independently of other generators is considered to be rare. For most usual generator applications, there is more than one generator operating in parallel to supply the power demanded by loads. In all major countries, hundreds and even thousands of generators are interconnected for hundreds of miles by transmission lines, forming the national grid supplying electrical energy to scattered loads. Industries having their own electric power generating stations usually add a generator parallel to the existing one(s) for their additional load demands rather than replacing it with a larger rating. Furthermore, multiple generator installation have become common in applications for standby, prime, portable, stationary, commercial and military power system; while they continue to grow [1]–[2]. During parallel operation, synchronous generators can act as frequency regulators (active power control) and as voltage regulators (reactive power control) to meet load requirements. Some of the major advantages of parallel operation (synchronization) of multi-generators can be summarized as [3]–[4]:

1. Ability to supply larger loads.
2. Increases the reliability of the overall system.
3. Minimizing the effect of unexpected load changes, interruption and shedding.
4. Allowing one or more of them to be removed for shutdown and preventive maintenance.
5. Increasing fuel efficiency and generators lifetime.
6. Introducing the recent concept of micro-grid and distributed generators (DG) power system.
7. Decreasing the overall cost.

(II) SHIP MICRO-GRID SYSTEM:

The electric power system in a ship resembles a smart micro-grid, and also has characteristics that make it unique. The electric power system in ships is designed to be autonomous, highly reliable and capable of delivering high quality power to all loads, and organized as a flexible distribution network that can be monitored and reconfigured depending on needs [5]. Shipboard loads, however, have characteristics and requirements that vary widely, ranging from continuous duty loads, like hotel loads and propulsion loads, to intermittent duty loads, such as directed energy weapons. For these reasons, the electric power system in a ship is likely to be characterized by highly reliable features.

A typical application of parallel operating multi-generators system within a ship is illustrated in Fig.1, where electric power is generated, for example by four 1000 kilowatt Ships Service Diesel Generator (SSDG) sets, with primary three-phase power distribution board of 450V and 60Hz. Normally, any two parallel units are capable of supplying the ship’s load during underway. However, in case of auxiliary propulsion motors operation (325HP each) three parallel units are required to carry all ship loads. Also, such ship micro-grid has a sub-distribution system of 450V and/or 120V with a frequency of 400Hz, for supplying navigation, communication systems, electronic equipments, servicing aircraft and landing craft, with their special voltage requirements, through static and dynamic frequency converters (as seen Fig.1).

It can be seen that, such class of ships having independent grids for their own load demands, while parallel operation is continuously done underway (away from utility) or while transferring to or from shore. Hence, such power distribution network can be considered as a typical micro-grid system.
Typical example of parallel operating system within a micro-grid of a specific class of ships.

(III) GENERATORS LOAD SHARING:

Generator units have to be run in parallel to share a total load that exceeds the capacity of a single machine. Changeover between units requires a brief parallel running period to achieve a smooth transition without blackout. Essentially, parallel running is achieved in two stages; synchronizing then load sharing. Usually, the check or synchronizer units are utilized to fulfill the four conditions of parallel operation (same voltage magnitude, same frequency, same sequences and no phase shift). Then another load sharing equipments are utilized. The total bus-bar load can now be shared between generators as the speed controls the active (P-Watt) power while the voltage excitation controls the reactive (Q-VAR) power [6].

Adjusting load sharing between generators is achieved by adjusting both speed and voltage droop characteristics, as depicted in Fig.2. Balance load sharing requires similar droop characteristics of machines or applied advanced control techniques to automatically compare between generators loading, via voltage and current transformers (CT and PT). Then, any differences are used to provide an error signal for the controllers to raise or lower generators speed and voltage droops [6].

Two forms of practical reactive compensation circuits can be utilized as depicted in Fig.3; first is parallel droop compensation, where each parallel droop circuit is independent of the other, and second is crosscurrent (differential) compensation, as the secondary current of the current transformer induces a voltage across the burden resistor of one generator is added as a vector to the line voltage of the other generator to produce an error signal to the automatic voltage regulator device (AVR), hence compensate for any difference in currents between generators.

For active power compensation, governors, which increases or decreases the speed (frequency) reference with a change in load demand, can be mechanically or electronically utilized in practical.
(IV) SYSTEM EQUATIONS:

The main objective of this paper is to investigate a proposed method to control the load sharing of two parallel generators using microcontroller based circuits in both speed (active) and volt excitation (reactive) control loops. Two motor-generator sets are utilized for simulation and experimental validation, as shown in Fig.4a, consists of:

- A main power supply of \( V_{2} \) and \( f_{2} \)
- Two V/f inverters for speed control with variable output of voltage and frequency (\( V_{m} \) and \( f_{m} \))
- Two 3-phase induction motors (IM)
- Two mechanical couplings
- Two 3-phase synchronous generators (SG)
- A 3-phase load of \( V_{l} \) and \( f_{l} \)
By controlling the induction motor speed through the V/F drive and the excitation of the synchronous generator, both supply frequency and voltage magnitude can be controlled and varied respectively to provide the 3-phase loads with their frequency and voltage requirements. Such system configuration is named as rotary frequency converter (RFC) [7], and the following steady state equations can be introduced, for each set:

For induction motor, based on approximate equivalent circuit shown in Fig.4b, the following equations can be written [8]:-

\[
T_m = 3 \left( \frac{V_m}{\omega_m} \right) \left( \frac{R_s}{\omega_m} \right) \left( \frac{1}{\omega_m R_s C_s} \right) = \left( X_{L2} + X_r \right) \omega_m
\]

(1)

\[
\omega_m = \frac{120 f_m}{P_m}
\]

(2)

\[
\omega = \omega_m - \omega_m
\]

(3)

For the mechanical coupling in Fig.4c:-

Figure (4): System under investigation
For the synchronous generator, based on approximate equivalent circuit shown in Fig.4d, the following equations can be written [8].

\[ \omega_m = \omega_{2g} = \frac{1}{f} \int [T_1m - T_g] \]

(4)

\[ T_g = \frac{\omega_{2g} T_2}{120} \]

(5)

\[ I_g = \frac{\omega_{2g} I_2}{120} \]

(6)

\[ V_r = V_f + j_1 I_2 \]

(7)

\[ V_f = R_{2g} \omega_{2g} \]

(8)

\[ P_2 = 3 \left( \frac{V_f}{T_2} \cos(\theta_2 - \theta) \right) - 3 \left( \frac{V_f}{T_2} \cos \theta_1 \right) \]

(9)

\[ Q_2 = 3 \left( \frac{V_f}{T_2} \sin(\theta_2 - \theta) \right) - 3 \left( \frac{V_f}{T_2} \sin \theta_1 \right) \]

(10)

For the feeding load in Fig.4a,

\[ P_1 = 3 V_1 I_1 \cos \theta_1 = P_{21} + P_{22} \]

(11)

\[ Q_1 = 3 V_1 I_1 \sin \theta_1 = Q_{21} + Q_{22} \]

(12)

From previous equations it can be seen that for stand alone RFC set, controlling field of the generator will control the generator voltage magnitude while controlling the speed of motor will control both generator output frequency and voltage. For parallel operated of the two RFCs, controlling field of the generator will control the reactive power while controlling the speed of motor will control the active power; and load sharing will be determined based on each set speed and voltage droop characteristics (as described in section III).

(V) SIMULATION ANALYSIS:

The system described in section (IV) has been simulated using Simulink under Matlab software program as depicted in Fig.5, while connected to a 3ph load through circuit breakers. The speeds and voltages of the generators have been adjusted by adjusting the V/F of the inverters and the firing angles of the controlled rectifiers for the field excitation, respectively [9]. Results have been obtained for such simulated set before and after synchronization of the two generators as depicted in figures 6 and 7.

(A) Before parallel:

Fig.6a shows phase voltages \( V_{g1} \) and \( V_{g2} \) versus time before parallel operation of the two generators, as voltages are out of phase and different in amplitude, where the two RFCs are not ready to be paralleled. Fig.6b shows the two phase voltages as they are adjusted to be almost in phase and same amplitude now. The RFC1 and RFC2 are ready to be paralleled. Fig.6c shows that, the RFC1 is carrying the load \( I_{g1} = I_l \) and RFC2 is carrying no load \( I_{g2} = \text{zero} \).
FIGURE (5): Simulink diagram of two parallel operated RFCs

(a) Generator voltages $V_{g1}$ and $V_{g2}$ are completely out of phase and unequal magnitude

(b) Generator voltages $V_{g1}$ and $V_{g2}$ after being adjusted to be just in phase and equal magnitude

(c) Generator currents $I_{g1}$ and $I_{g2}$

Figure (6): Simulation results before parallel operation
(B) After parallel:

Fig.7a shows phase voltage of the main bus of parallel generators versus time (in the upper graph), while the figure also shows unbalanced load currents delivered from the two generators (in the lower graph). That means the existence of a circulating current between the two generators. Fig. 7b shows almost balanced load sharing by adjusting the frequency (speed droop) and field excitation (voltage droop) of RFC2 generator to be almost equal to the other RFC1. Hence almost equally load sharing of the required active and reactive load power is fulfilled.

(V) EXPERIMENTAL VALIDATION:

A general schematic block diagram of the implemented setup, including power and control circuits, can be seen in Fig.8a, while a photograph of the experimental setup with different utilized units can be found in Fig.8b, where two rotary frequency converters (RFC1 and RFC2) have been integrated and operating in parallel. Two 3ph induction motors, each of 1.5hp 220V 50Hz 4poles, and two 3ph synchronous generators, each of 1kW 220V 50Hz 4poles, have been utilized to form the prototype setup. Two 3ph 1.5kW commercial inverters (V/F VSD s) are utilized for frequency changing by introducing microcontroller based (PIC 16F877) closed loop control circuit operating as active power control modules (speed droop). Two 220V 1A AC to DC uncontrolled rectifier associated with two PWM controlled DC to DC chopper have been designed and implemented based on microcontrollers for generators excitation changing, hence operating as reactive power control modules (voltage droop). A synchroscope unit has been used for manual synchronization of the two units. The input voltage of each RFC is 220V 50 Hz, while the required output load voltage is 115V 60 Hz. The setup has been tested and different experimental waveforms have been obtained using digital scope for two modes of operation: open loop and closed loop.
(a) Overall block diagram

Figure (8): The implemented setup

(b) A photograph

Set up of a practical experiment for two parallel closed loop Rotary frequency converters feeding load
(A) Open loop mode (no speed or voltage feedback):
Within this mode, the setup has been operated to provide the following functions:
(i) Synchronization: where SG1 is carrying 1.4A load and SG2 (incoming RFC) is carrying no load. SG2 speed and voltage are manually adjusted to achieve parallel conditions (same voltage magnitude, same frequency, same phase sequence and no phase shift). The output waveforms are taken before and after synchronization as depicted in figures 9 and 10, respectively.
(ii) Load sharing: as a manual adjusting of the system is done manually to achieve balanced load sharing and to carry more loads under active and reactive droop methods, as discussed in section III.
From figures 9 and 10 it can be seen that:-
• As output voltages and frequencies of the two generators are unequal and are out of phase, the parallel conditions are not achieved, as shown in Fig. 9a.
• When output voltages and frequencies of the two generators are adjusted and become equal and are almost in phase, parallel conditions are achieved, see Fig. 9b.
• Load current is not shared, as SG1 is carrying the whole entire load while SG2 is not synchronized and carrying zero current, as shown in Fig. 9c.
• After synchronization, SG1 and SG2 are paralleled, with the same load voltage, and share same load current (1.6A), as depicted in Fig. 10c.
• Load voltage is increased after parallel process, as shown in Fig. 10a, since both generator voltages are increased due to current load sharing and no compensation for voltage regulation within such open loop mode of operation.

(B) Closed loop mode (microcontroller based speed and voltage feedback):
Within this mode, the setup has been operated to provide the following functions:
(i) Synchronization: as SG1 is carrying 1.9 A load and SG2 (incoming RFC) no load, while the speed and the voltage are automatically adjusted by the implemented microcontroller based reactive and active modules to achieve parallel conditions, and the waveforms are obtained after and before synchronization.
(ii) Load sharing: as speeds and voltages of the generators are automatically adjusted, for balanced and equal load sharing using the PIC16877 microcontroller modules, hence providing advanced droop compensation method for both active and reactive power load sharing.

It should be noted that within each RFC set, for voltage droop compensation, the microcontroller algorithm (written in C program) is based on sensing the output voltage of the generator and then compared with the given reference value to increment or decrement, within hysteresis band, the duty cycle of the PWM controlled DC chopper for the field excitation module. Same process is done for the speed droop compensation, by sensing the coupling shaft speed and then compared with the given reference value to increment or decrement, within hysteresis band, the reference value of the V/f inverter speed control drive.

A comparison between experimental results obtained for both open loop and proposed microcontroller based closed loop operation is depicted in Fig.11, where it can be seen that:-
• The setup provides sinusoidal output voltages with voltage controllable range of magnitude and frequency, without the need of any filters in the output load circuit, see Fig. 11a.
• The accurate and symmetric automatic compensation of voltage magnitude due to voltage closed loop circuit resulted in not only better automatic reactive load sharing but also allowing 30% increase in load current value due to the compensation of the voltage droop, see Fig. 11b.
• The most advantage achieved within the proposed closed loop circuits can be noticed in the shape of load voltage as only 10% voltage droop are achieved compared to 30% for the open loop due to the feedback compensation, see Fig. 10c.
Introducing the microcontroller in both voltage and speed control loops provides the setup with good and solid voltage and frequency compensation for sudden load changes and both active and reactive load sharing between generators is automatically achieved.

Figure (9): Experimental waveforms within open loop operation before synchronization

Figure (10): Experimental waveforms within open loop operation after synchronization

Figure (11): Comparison between parallel operation within open loop and closed loop operating modes

(VI) CONCLUSIONS:
The paper presents an advanced droop method, based on microcontrollers, for both active and reactive load sharing of parallel operated generators. The proposed setup has been investigated by simulation analysis and experimental validation for proof of concept. The overall proposed setup can be introduced
as a simple micro-grid system practically for ship requesting. It can be used not only to share loads between many generators but also can control both the output voltage amplitude (using voltage control module) and frequency (using speed control module). This forms a set of parallel operating rotary frequency converters which is very important in ship demands, such as converting the incoming 220V 50Hz to feed loads of 115V 60Hz or other requirements. Since both voltage and speed are automatically controlled, simple synchronization and load sharing of both active and reactive power can be easily achieved. The proposal can be extended to cover more than two generating units (as a micro-grid system) and also can be modified (by adjusting the voltage and speed references) to work and tested for generators with different ratings.
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