DSP-Based Simple Technique for Synchronization of 3 phase Alternators with Active and Reactive Power Load Sharing

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***Abstract* — Automatic coupling of 3 phase synchronous alternators to infinite bus AC grid has been discussed and studied, analytically and practically as a case study, to deepen concept of distributed alternators control. The paper introduces an experimental setup for alternator synchronization with active and reactive power control scheme, as a laboratory guide to be followed by engineers in real power stations or in distributed generation. Through Matlab Simulink simulation analysis and practical results based on digital signal processor, the proposed prototype setups have been evaluated for different operation scenarios.**

***Index Terms* –** Alternator, DSP, experimental, load sharing, power control, synchronization.

I. INTRODUCTION

The improvements of the conventional AC grid were exercised on its power quality [1], improved distribution and more robust protection and management schemes [2]. However, the concept of the conventional AC grid is still intact, such as a 3 phase synchronous alternator to be coupled with an AC grid with recent distributed generation (DG) systems [3]. For the investigated system, DC voltage choppers [4] have been used for controlling the field of the alternator and its speed to control both reactive and active power [5][6]. Such setup requires pulse width modulation (PWM) and feedback signals from the alternator [7], which have been monitored and managed with a Texas Instruments digital signal processor (EZ-DSP 28335), using least number of sensors.

II. AUTOMATIC SYNCHRONIZATION WITH ACTIVE AND REACTIVE POWER CONTROL

Analytically, active power (P) control is performed by manipulating the power angle (δ), which is the phase shift between AC grid (V_{AG}) and alternator voltage (V_A) signals; hence current is injected through line reactance (X) in unity power factor mode (UPF); using (1):

$$P = \frac{3\, V_{AG} V_A}{X} \sin\delta \qquad (1)$$

Concerning analytical reactive power (Q) control, it adopts the idea of voltage magnitude control wherever reactive power level needs to be modified. Such concept is performed according to (2):

$$Q = \left(\frac{3\, V_{AG} V_A}{X} \cos\delta\right) - \left(\frac{3\, {V_A}^2}{X}\right) \qquad (2)$$

Simulation analysis using Matlab Simulink has been carried out to verify the control algorithm defined by the flow chart depicted in Fig. 7 for all modes of operation.

III. SIMULATION

The proposed system is simulated according to single line diagram of Fig. 1 and consists of a three-phase alternator that should be synchronized and tied with a three-phase infinite bus AC grid of voltage (V_{AG}). In between, there is a three-phase load that will show the effectiveness of the active and reactive power controller over load sharing. Other peripherals have been used such as a controller to synchronize alternator to grid as in Fig. 2 and power control blocks to control active and reactive power over the alternator as seen in Fig. 3.

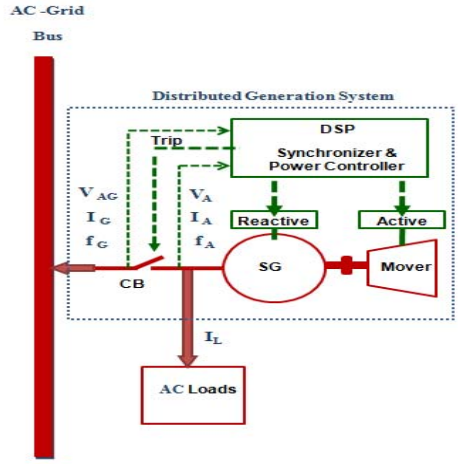


Fig. 1. Single line diagram.

In Fig. 2, two AC voltage transducers have been used to get a voltage signal over the AC grid and the alternator. Signals have been analyzed into a magnitude; and into angle using a phase locked loop simulation block (PLL). Both magnitudes and angles are compared to get an error value necessary for the field and speed controllers over the alternator, in order to synchronize it with grid.

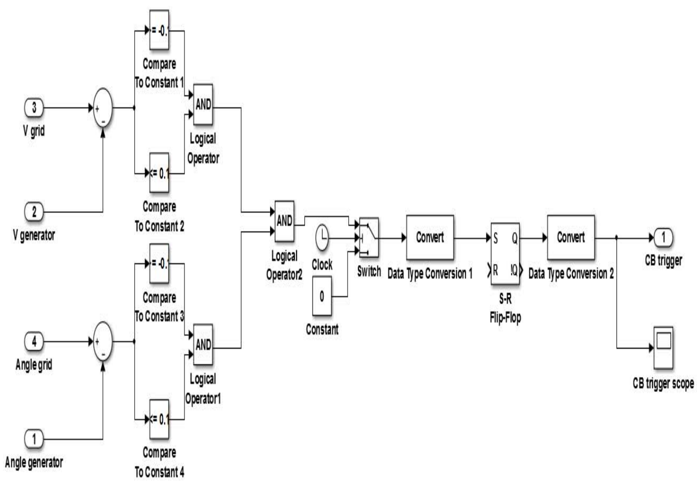


Fig. 2. Synchronizing unit simulation.

After synchronization, power controller takes charge of further actions, like sharing load power with the AC grid or injecting the AC grid with active and/or reactive power when needed. The controller requires an extra AC current transducer, installed on alternator output, to be used for active and reactive power calculation, necessary for controller feedback as in Fig. 3.

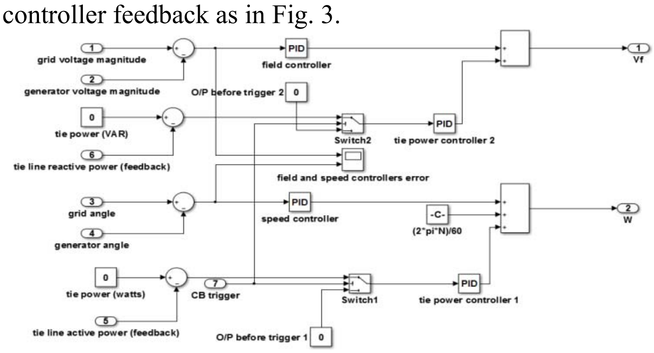


Fig. 3. Active and reactive power controller simulation.

Both of the synchronizing unit and the power controller follows the algorithm explained in Fig. 7, as it would be practically applied and programmed to the Texas Instruments DSP.

IV. SIMULATION RESULTS

The alternator used in setup and in simulation has 4 poles, so it is driven to rotate at 1500 RPM, in order to be synchronized with a 50 Hz AC grid as seen in Fig. 4.

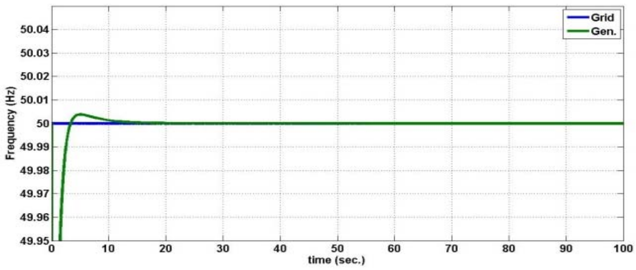


Fig. 4. Grid versus alternator frequency.

Fig. 5 shows the alternator operating in UPF as a current of 2.269 A (1500 W at 220 V_φ) is supplied to a standalone load before synchronization action; while in Fig. 6, after synchronization, current supplied by alternator is increased to 4.539 A (3000 W at 220 V_φ) as the alternator contributes for load sharing with the AC grid as well, reducing the AC grid load burden.

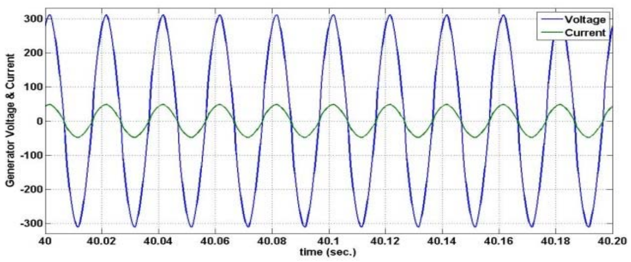


Fig. 5. Alternator supplies load.

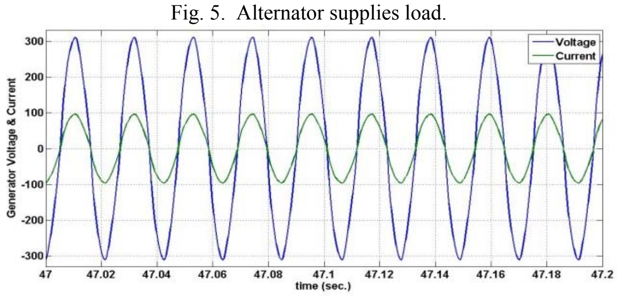


Fig. 6. Alternator supplies load and inject active power to AC grid.

V. EXPERIMENTAL VALIDATION AND RESULTS

This section will discuss the main components that have been used to get an experimental setup; which is required for validating the concept of power control and loading sharing.

A. Algorithm and program

In order to synchronize the alternator to AC grid and control its active and reactive power, control blocks have been created for such purpose as in Fig. 8, in order to be downloaded into the DSP. The control algorithm that such control blocks follow is shown in Fig. 7 where feedback signals are digitally filtered, conditioned and used for the control scheme.

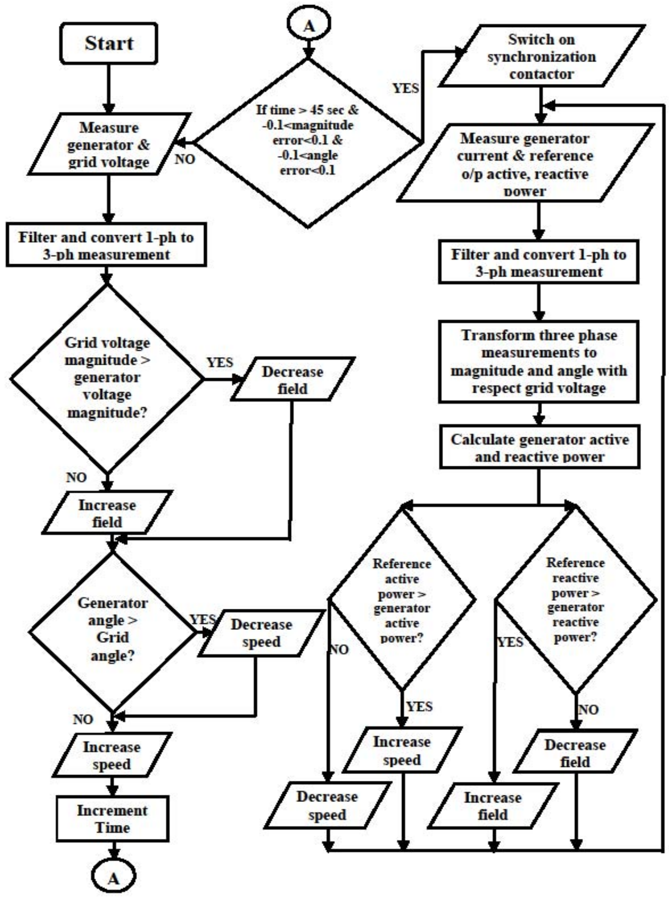


Fig. 7. DSP program flowchart.

Control blocks have the same structure as simulation program of section III and as seen in Fig. 1, because simulation was already based on practical setup considerations, to get corresponding simulation and practical results for proof of concept. Both of simulation and practical validation follow the algorithm shown in Fig. 7.

Fig. 8 explains that the DSP has an analog to digital converter (ADC) which produces digital values for AC grid voltage and current, same for alternator. Also a digital reference value for active and reactive power set by external analog knobs. All of these digital values for voltage and currents are converted back to analog then processed by the PLLs into two separate values, voltage magnitude and phase shift. Voltage magnitudes and phase shifts of alternator and grid are used first for synchronization then for active and reactive power control. These magnitudes and phase shifts are used as compare signals for the PI controllers.

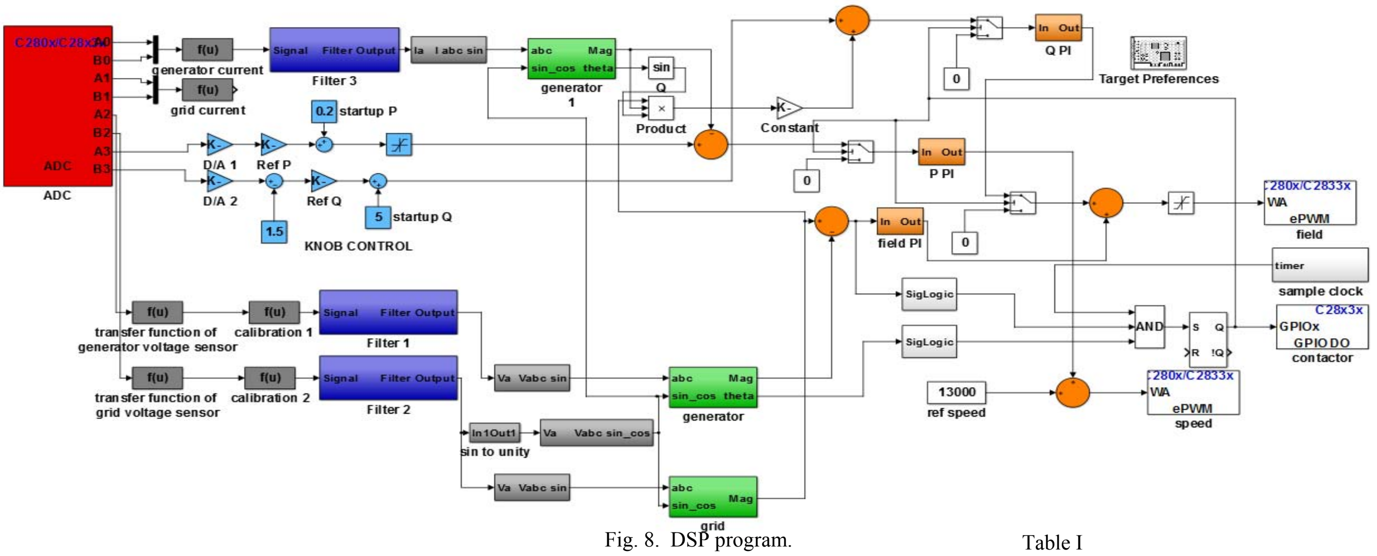


Fig. 8. DSP program.

The control strategy is built on simple closed loop control scheme with feedback, and the error signal is what decides the control actions, with a PI controller. The DSP works on producing a PWM signal over the two chopper circuits, which one control the alternator speed while the other controls field voltage; hence the active and reactive power of the alternator and its tie line power flow with AC grid.

Feed forward control has been introduced to provide more dynamic and simpler control scheme. Feed forward is a term describing an element or pathway within a control system which passes a controlling signal from a source in its external environment, which is in this case a constant digital number. This constant number (i.e. ref. speed = 13000 in Fig. 8 is corresponding to the sampling number required by the DSP PWM block in order to control the DC/DC step down chopper which by its turn control DC motor speed, up to 1500 RPM, which is the speed for a 4 pole AC alternator to generate a 50 Hz power signal. Certainly such number isn't exact all time due to variable electric and physical characteristics of the IGBT and the DC motor (temperature, dV/dt, mechanical friction, etc…); here comes the advantage of feed forward control that works continuously on adding or subtracting to "13000 samples" to stabilize the speed at 1500 RPM, which means an active power control as well since it is related to speed control. The value of feed forward control is produces by the power PI controller.

There are three PI controllers, one for the active power control (speed control) which gets its error signal from comparing active power knob with alternator feedback current magnitude. The second PI is for field control, only used for synchronization at first then works only afterwards on providing a fixed field signal. It gets its error signal from comparing the AC grid and alternator voltage magnitudes. The third PI is for reactive power control, and it works side-by-side with the field PI controller by adding or subtracting over its fixed field signal (another feed forward control) in order to produce the desired field coil current, suitable for the desired reactive power. The reactive power PI controller gets its error signal by comparing the alternator current phase shift with the reactive power knob reference value.

There are differences found between the proportional and integral gains (K_P and K_I) of the previously discussed PI controllers - in case of practical and simulation studies - due to electric and physical characteristics that have been discussed earlier. These values are demonstrated in the following table I.

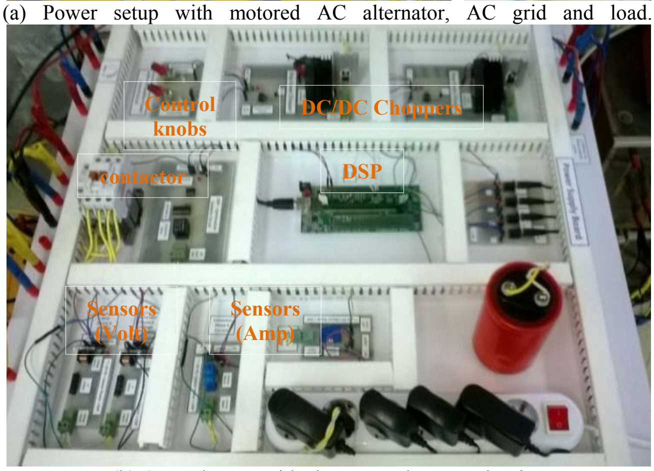
Table I
PI CONTROLLERS' PARAMETERS FOR SIMULATION SOFTWARE AND PRACTICAL SETUP.

PI Controller	Simulation parameters		Practical parameters	
	K_P	K_I	K_P	K_I
Speed (active power)	7	15	12	16
Field	7	15	39	64
Reactive power	3	8	14	18

B. *Experimental validation*

An experimental setup based on a synchronous alternator has been utilized to validate the concept of active and reactive control for load sharing over an AC grid, as shown in Fig. 9.a. A complete control setup based on DSP has been designed and implemented as shown in Fig. 9.b. It should be noted that a diesel engine has been substituted with a high inertia (flywheel) DC motor, with implemented variable speed chopper based armature drive circuit has been utilized for speed control of the alternator (hence the active power), while another excitation field control chopper circuit has been used for reactive control.

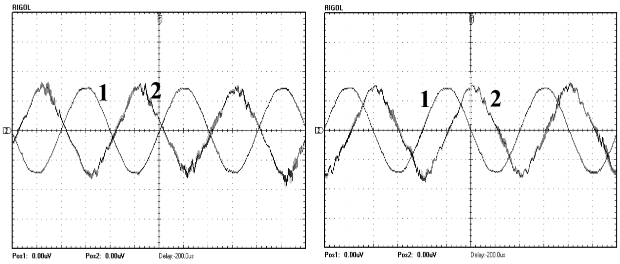
(a) Power setup with motored AC alternator, AC grid and load.



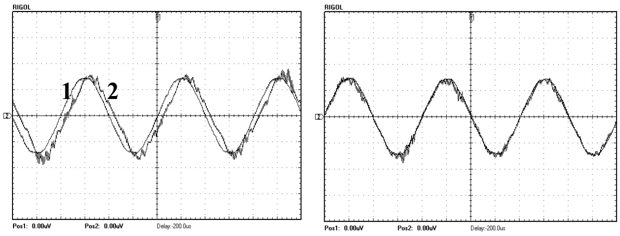
(b) Control setup with chopper and sensor circuits.
Fig. 9. Overall practical setup for alternator with AC grid.

C. *Experimental results*

Fig. 10 shows the practical results of the alternator trying to synchronize with the grid, making its output voltage, phase angle and frequency measured same as grid. From Fig. 10.a to Fig. 10.d, the alternator output voltage is getting closer to AC grid voltage.



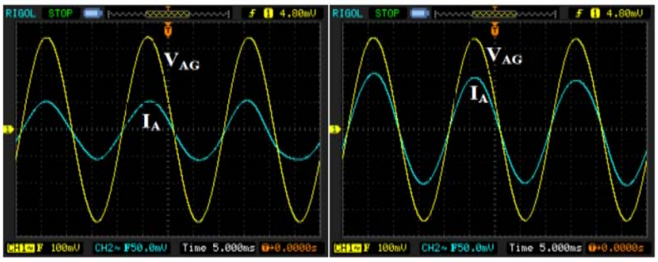
(a) Grid[(1)] and alternator[(2)] volts out of phase. (b) Grid and alternator are getting in phase.



(c) Field PI controller minimizing phase shift. (d) Grid and alternator voltages synchronized (V_{AG}).

Fig. 10. Steps to minimize phase shift between grid and alternator voltages.

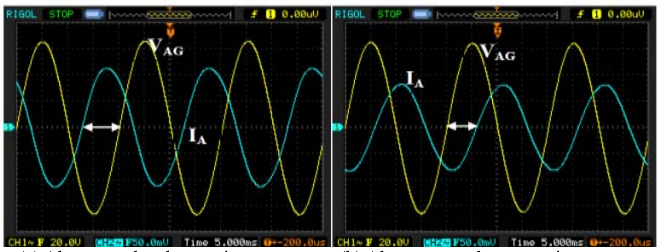
All of the following figures are taken directly from oscciloscope, where signal in yellow is alternator – grid synchronized voltage (V_{AG}) and blue is alternator output current (I_A) . Fig. 11.a and Fig. 11.b are the same case of the simulated results given in Fig. 5 and Fig. 6 respectively, where the alternator is supplying active power to load only as in Fig. 11.a and then asked to produce more, in order to be injected to the AC grid as in Fig. 11.b.



(a) Alternator supplies load only. (b) Alternator supplies load and grid.

Fig. 11. Active power control.

The reactive power controller is able to produce and inject reactive power to AC grid at different levels, it can withdraw reactive power as seen in Fig. 12.a or it can produce reactive power as seen in Fig. 12.b. Reactive power controller operation is based on feedback phase shift of alternator output current, referred to V_{AG}.



(a) Alternator absorbs reactive power. (b) Alternator produces reactive power.

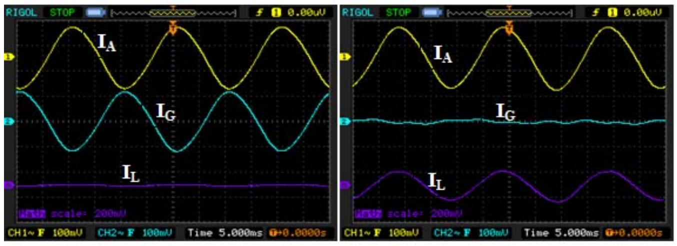
Fig. 12. Alternator reactive power control.

Finally, Fig. 13 shows the ability of the active power controller on load sharing between alternator and AC grid. The upper yellow signal is the alternator output current (I_A), that's in middle (blue) is the AC grid current (I_G) and the lower velvet signal is AC resistive load current (I_L), which has been increased three times to show system ability on load sharing, general performance and dynamics [8].

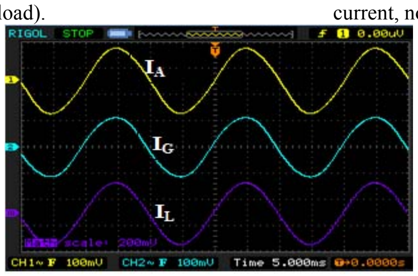
Fig. 13.a is a case of no load, so the alternator output current is all injected to AC grid, which explains why their current signals are opposite.

Fig. 13.b is a case where the load took all the alternator active power output, leaving the AC grid no current to take.

Finally, Fig. 13.c shows that the AC load power is doubled, which means that the alternator cannot supply it alone. Current is withdrawn from AC grid to compensate the difference. It would be noticed by having all three currents in phase.



(a) All current injected to grid (no load). (b) Load requires full alternator current, none to grid.



(c) Load sharing case: current from both alternator and grid to load.

Fig. 13. Alternator & grid sharing AC load.

From the obtained results, it's to be observed that automatic synchronization of the alternator has been achieved with the capability of active and power control and load sharing.

VI. CONCLUSION

In this paper, a simple yet effective technique for digital synchronization of an alternator to the grid has been presented. Moreover, the technique enabled control over active and reactive power delivered to the grid through the alternator. The presented results illustrate the system operation over wide range of references ensuring the stability of the system. The simplicity of the algorithm, low cost hardware requirements and results reveal the novelty and effectiveness of the proposed system. Further investigation into increasing synchronization speed and using switching filters for alternator field can be considered for achieving a much more effective system in the future investigation.

VII. REFERENCES

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