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Controller Design for Synchronizing Distributed Generation Systems with the Phase Locked Loop (PLL)

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Abstract—*In this paper a fuel cell power plant design using phase locked loop method for paralleling a fuel cell with the global network is described. Despite the fact that synchronous systems for scattering generation sources like generators have been used in Iran's plants, but there has been made fewer efforts in the case of plants based on fuel cell. In this paper an approach is presented for synchronization based on PLL that can reduce the response time to less than 2 seconds and time difference becomes zero in less than 3 seconds. Using the relay auto tuning algorithm in the closed loop system, the frequency fluctuations become less than 0.05% at the output. As in this approach, tuning is based on the DC voltage level, the induction property that makes the PID controller be unstable is reduced and we will have a very stable output wave. This is the main advantage of this controller.*

Presented control structure is made up of three loops, whichwe will reached frequency to reference frequency by use of first loop and in the next loop we do it's phasecontrol whit take an integration of frequency, and in the frequencies difference less than 1 Hz. Presented control structure is made up of three loops. Using first loop, the frequency is reached near the reference value and in the next loop the phase is controlled by integration of the frequency, and in the frequency differences less than 1 Hz, the third loops does control frequency in independent way from the phase. Another advantage of this method is that the circuit remains in phase locked state when the phase has been synchronized, and there is no need to consider the time of connection to the network, and finally the output fluctuation is brought into zero. In this paper, it is also built an empirical example of digital synchronizer which is efficient in synchronizing distributed generation systems with the phase locked loop and will be described in detail in continuation.

Index Terms— Phase locked loop, synchronizer, parallel and fuel cell.

I. INTRODUCTION

Use of scattering generation sources based on fuel cell, photoelectric cell and similar cases and also study about parallelism of these sources with the global network have been taken into little consideration in industrial applications and scientific research especially in Iran.

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But in practice we use from big energy generators such as high power generators and connive from all of the parallel advantages. It is often due to heavy damages to scattering generation sources that may be caused by parallelism and also non-spreading exploitation of these sources and using synchronous systems.

Establishment of four terms in below is necessary to reach this goal.

A. The same voltage level of phases
B. The same sequence of phases in the both sides of circuit breaker
C. Equivalence of frequency
D. Equivalence of namesake voltage phase in the connection time

II. THE SYNCHRONOUS

The manual's synchronous:

In this way after the voltage and frequency were the same, an operator, in attention to movement of synchroscop's and, he connects the breaker when the hand of synchroscope is on zero which in this way, there exists the possibility of operator error in paralleling the sources.

The microprocessor synchronizer set that was built in the laboratorial form in power investigation center is used in this experimental research. The result of necessary measuring time for synchronizing with this sample, according to maximum voltage difference and frequency slip and phase difference on both side is shown in table 1[8].

TABLE I. TEST RESULTS OF CLASSICAL SYNCHRONIZER

Set Parameter	Case 1	Case 2	Case 3	Case 4
ΔV%	2	2	2	2
S%	0.15	0.15	0.15	0.15
Δθ	0	1	2	3
Tsync	16min	1.6min	1.43min	0.82min

According to above results, it can be concluded that the main drawback of this device is that by increasing the required accuracy and decreasing the desired low-frequency difference, the time which lasts so that two generate source take a desired phase difference becomes very much while the connecting time is of key importance.

In phase parallel method for fast synchronizer system that was implemented in the company Laybyd [7], phase locking is a control method in which the frequency and phase are corrected simultaneously. The main advantage of this method is that phase and frequency can be corrected.

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The disadvantage of this method is that the control parameters are obtained in the particular circumstances of the case and there would be continuously low volatility. In this paper, by modifying the structure of detector and also by using relay PID auto tuning model, time synchronization of sources is reduced and stability is improved.

III. PHASE LOCKED LOOP METHOD

In this method, there is no need to find same phase moment and synchronizing is done with more fast and confidence. The idea of this method is similar to the PLL approach which has the most application in detection circuitry in the telecommunications and electronics and the block diagram of related chip is shown in figure 1.The first part of this chip is the phase detector that shows the phase difference between the produced signal with the reference signal and the second part is a low pass filter which shows the difference value in the form of DC voltage to the VCO part which is a voltage-controlled oscillator. The basic of PLL is that input voltage (VCO) is increased by lag phase but it is decreased by lead phase which finally becomes equal in the phase and the frequency.

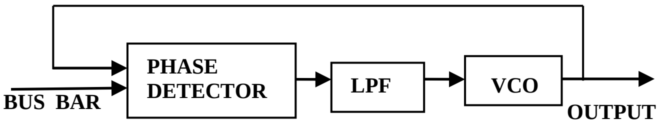

Figure 1. Block diagram of the PLL chip

In attention to block diagram in figure 2 the VCO set consists of: controller, invertor, DC convertor, hydrogen valve and fuel cell.

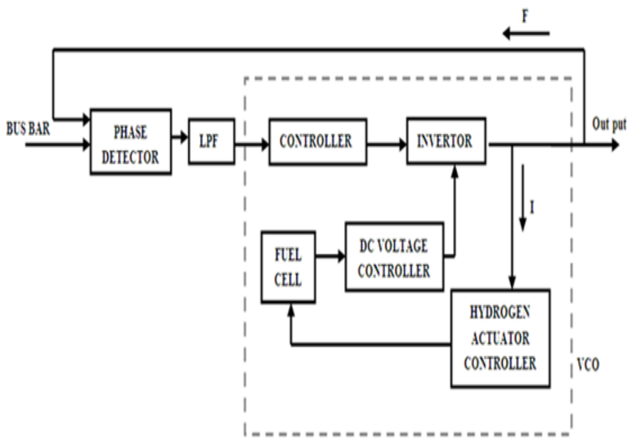

Figure 2. Block diagram of synchronizer fuel cell

In this part (VCO), at first takes a sample from current and which is then sent to hydrogen fuel valve and the amount of transmitted hydrogen to fuel cell can be increased and decreased by controlling this valve. As this DC voltage has a low value, its value is increased by the DC/DC convertor and then is applied to the invertor which turns to AC voltage after the invertor. The synchronizer block consists of two control directors that control the frequency in the first loop and the current amplitude in the second loop and the frequency and current are corrected simultaneously at the end of the approach.

IV. PHASE DIFFERENCE IDENTIFIER DYNAMIC'S MODEL

The difference between phase locking is related to the type of phase detector which depends on the phase identifier that can take various values such as RS-FF, AND, XOR and the chip 4046 and can be also of hysteresis type that each one can has its own specific advantage. Chip 4046 is used in this paper which is shown in Figure 3. This chip is a phase difference chip and acts in rising positive edge and is not sensitive to duty cycle.

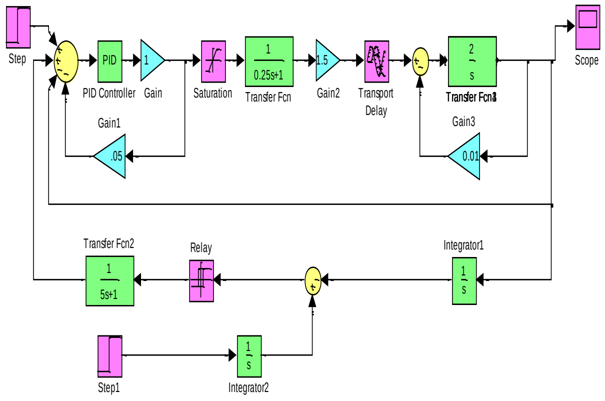

Figure 3. Dynamical model of synchronizer

V. DYNAMICAL MODEL OF SYNCHRONIZING SET

Figure 3 contains the synchronizing set and fuel cell inverter dynamical model which shows the output of detector in digital form, by comparing the phase of cell with the phase of output bus bar.

After passing it through a filter, sharp edges of the waveform are softened and by commanding again to the hydrogen fuel control valve, the fuel cell output voltage is controlled. Phase of fuel cell signal is obtained from the integral of inverter output frequency signal and zero steady state error in the fuel cell inverter output frequency and phase reference signal will be the same. The phase correction leads to the correct frequency.[7]

$$\Delta\theta = 2\pi\,(f_1 - f_2).t + (\theta_1 - \theta_2) \quad (1)$$

$$\frac{d\Delta\theta}{dt} = 2\pi\,(f_1 - f_2)$$

$$V_{out} = k\Delta\theta + C$$

In figure 3 velocity control is done in the first loop and the phase control is done in the second loop so that frequency difference between two systems will be 1Hz, which is shown in figure 4.

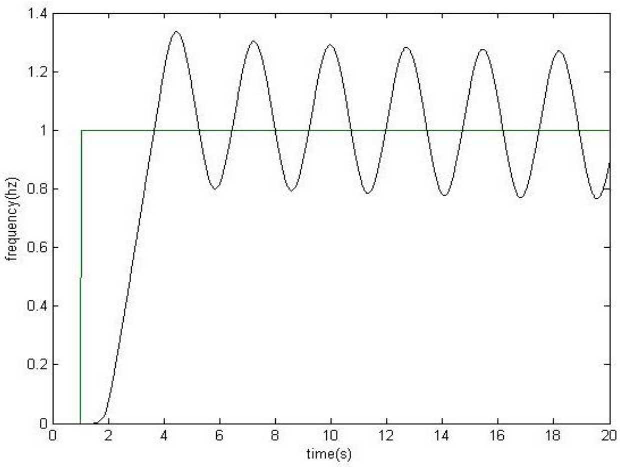

Figure 4. Changes in the frequency near to 1 Hz

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Now for reducing the frequency difference less than 1Hz, third loop starts working. According to figure 5 the output frequency in this loop is compared with the reference frequency directly, in which the fuel cell frequency is corrected independently of its phase so that by getting to the acceptable frequency difference, the PLL method works well and do the correction of phase and frequency. Finally frequency changes is reached to least amount according to figure 6.

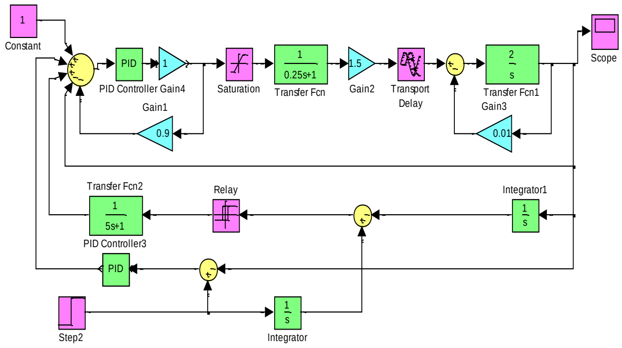

Figure 5. Synchronizer dynamical model

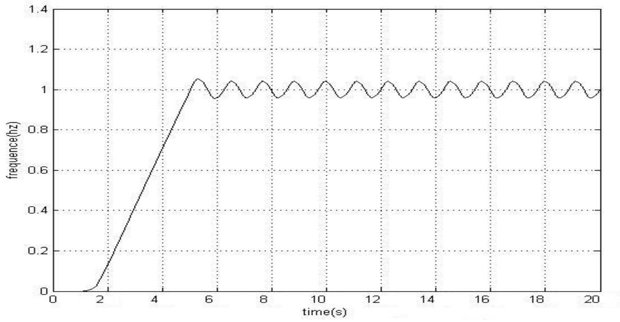

Figure 6. Variation frequency tuning PID

According to output wave form in the stable state we have a little fluctuation and the synchronizing time has been reached to 5 sec, too. We also use the relay auto tuning method for improving the output stability and for decreasing synchronizing time firs we examine results that obtained from ZVS method, before explain the relay auto tuning system in dynamic model show in figure 7. At first we examine results that obtained from ZVS method. In dynamical model shown in figure 7, first two signals pass from a NAND gate and then by use of a convertor, digital is converted to analog and then this signal is sent to control system. However, we have not a very desirable output response, as shown in figure 8.

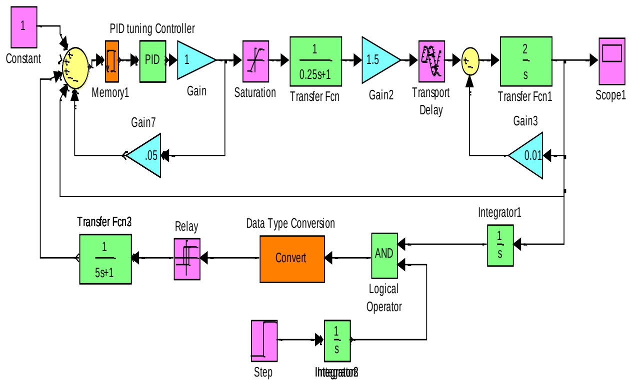

Figure 7. Synchronizer dynamic model of the ZVS

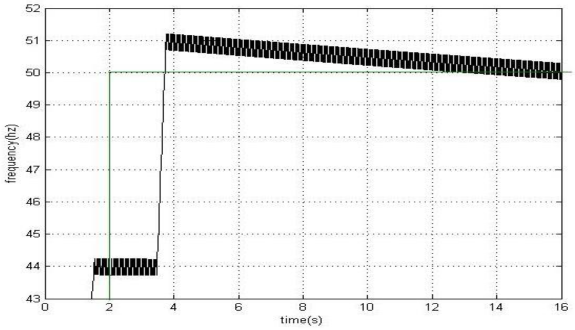

Figure 8 . Frequency variations with ZVSu

VI. AUTO TUNING ALGORITHM

According to figure 9, which is associated to the auto tuning structure that works on the bases of an on/off relay, which if difference between output and input be positive, the relay is on and when this difference be negative the relay stays in off mode[7]. Of course by changing DC level, the rate of changing is settled in stable state. One of the other advantages of relay auto tuning is that since this controller acts based on applied voltage level, in the circuits that work by invertor, the phase difference rate between voltage and current becomes minimum amount and it makes the output stability at the maximum case.

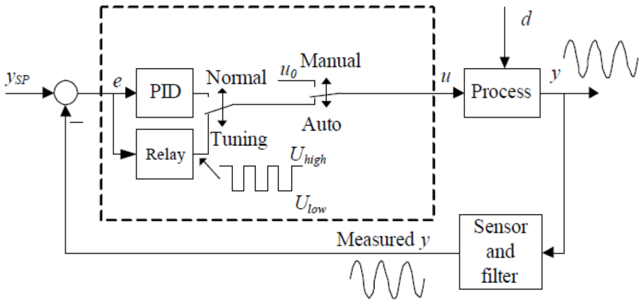

Figure 9. PID autotuning Structures based on control (on / off) of Relay

In this circuit by starting the phase difference, the controller relay turns the controllers on and off. These controllers calculate the PID control parameters by using fluctuation's amplitude and period in each loop automatically. To obtain adequate information for TUEND's coefficients, just some period times are required.

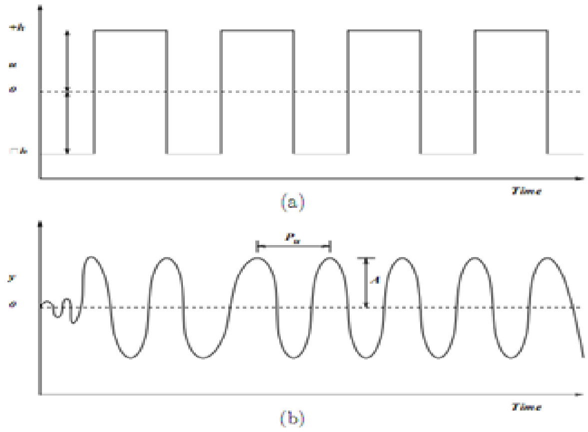

Figure 10.The effect of fluctuations on / off a relay.

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In the figure 10, when relay tuning turns on and off, the fluctuation occurs in the loop. Now by considering: A, ρ_u and h, the parameters of V_u and P, PI and PID are obtained.

$$k_u = \frac{4h}{\pi A}$$

Table 2 . Coefficients of Relay PID

	K_c	T_1	T_2
P	$0.5K_{CU}$		
PI	$0.45K_{CU}$	$P_U/1.2$	
PID	$0.6K_{CU}$	$P_U/2$	$P_U/8$

VII. CIRCUIT PSPICE

As it is shown in Figure 10, the voltage of the comparator to detect zero crossing is used to compare the surface of the earth that we have. Sinusoidal voltage is increased from zero level and the output of comparator and the reduction of the level of its output will be 12 and zero volts, respectively. For a wave with the sharp edges of the chip we have used two consecutive Schmitt Triggers to have in phase structure. As indicated in Figure 12, the amount of phase is characterized by an XOR chip. Depending on the phase I or phase of the signal generator to the grid voltage, the output of Flip Flop will have zero or one.

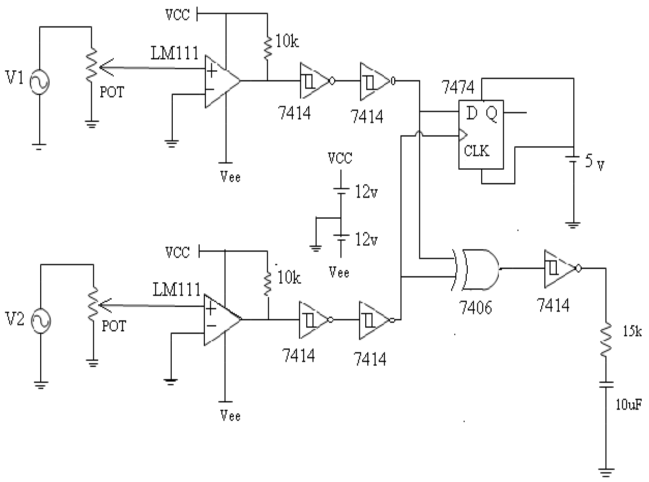


Figure 11. Synchronizer circuit Schematic

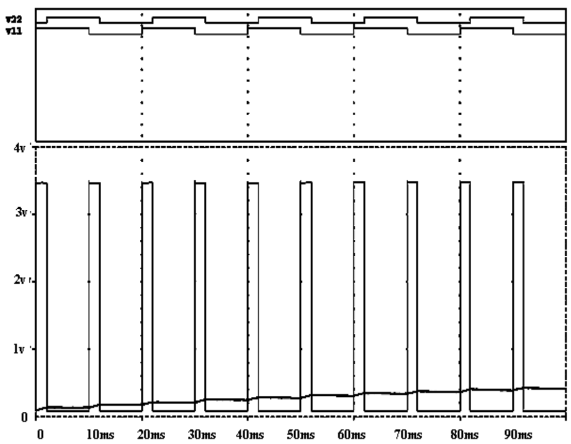
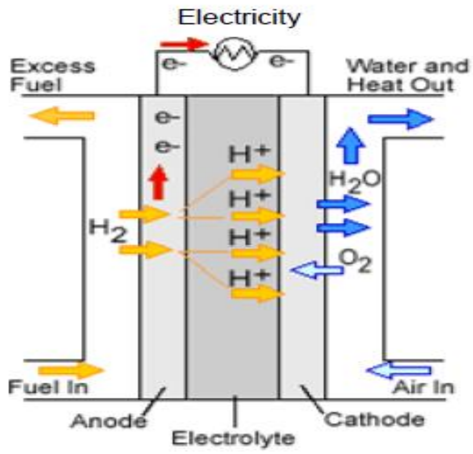


Figure 12. Response synchronizer circuit Schematic

VIII. THE GENERAL SYSTEM CHARACTERISTIC

This system is made up of 130 PEMFC's fuel cell, "Stuart energy", DC/DC power converter, DC/AC power converter, super capacitor and two PID controllers. The cells of the fuel cell are connected to each other in series and distinct form, the output current of fuel cell can vary between 0-25A ranges. The mass flow rate of input hydrogen and oxygen to the fuel cell is adjusted by PID controllers so that fuel cell set voltage is fixed at 96 V. In the ordinary fuel cell, anode is fed by gas fuels continuously and oxidant material is applied to cathode continuously.



The chemical reactions are happened in the electrodes in presence of catalysis and an electrical current is generated in the external circuit. There are various approaches for modeling PEMFC [2].

IX. FUEL CELL SYSTEM CONFIGURATIONS

The simplest form of fuel system configuration, as shown in Figure 12, consists of a fuel system stack followed by the DC-AC converter. If the isolation or a high ratio of the voltage conversion is required, a transformer is usually integrated into the system. The main drawback for this configuration is that the low-frequency transformer placed at the output of the inverter makes the system very bulky and expensive (Blaabjerg et al. 2004).

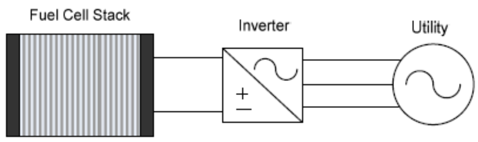


Figure 14. Fuel cell system configuration with a single inverter

A DC-DC converter is usually put between the fuel cell and the inverter, as shown in Figure 31. The DC-DC converter performs two functions: 1) it acts as the DC isolation for the inverter; and 2) it produces sufficient voltage for the inverter input so that the required magnitude of the AC voltage can be produced (Blaabjerg et al. 2004). The inverter can be single-phase or three-phase depending on the utility connection.

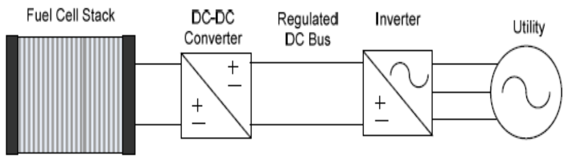


Figure 15. Fuel cell system configuration with cascaded DC-DC and DC-AC converters.

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A power conditioning system for a fuel cell with a DC-DC converter and a DC-AC inverter can be constructed with a combination of the converters discussed above. An example of a fuel cell system with power electronics interfacing into a three-phase utility system is shown in Figure 13, where an isolated DC-DC bridge converter and a three-phase hard switching voltage-source inverter are used [2].

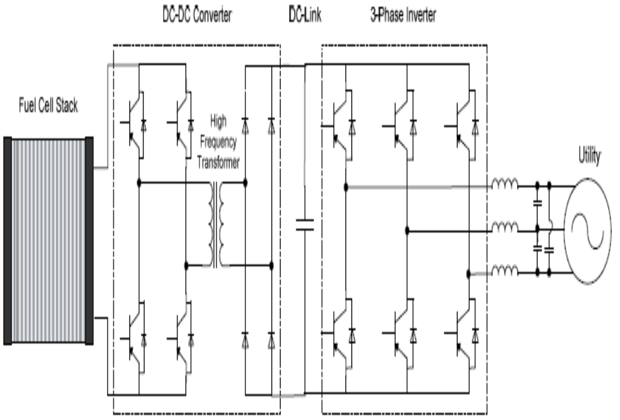

Figure 16. Cascaded DC-DC and DC-AC converter topology (DC-link)

X. DC/DC POWER CONVERTOR

This convertor is made up of two parts: the first stage includes a boost convertor witch converts the variable DC value when it is parallel with a high capacity capacitor bank. From fuel cell to higher and constant DC voltage value here this convertor controls by a PID auto tuning controller so that bus's high voltage is fixed on 200V. This problem is solved by adjusting "D", which obtain from below equation:

$$\frac{Vboost}{Vucap} = \frac{1}{1-D} \qquad (2)$$

XI. DC/AC POWER CONVERTOR

Since this system acts with the network coherently, use of a controlled invertor with current versus voltage control method in which the controller acts independently of network. The performance of controller is based on PWM which entirely adjust frequency at 50 Hz and voltage level at 220V. Triangle carrier wave frequency is equal with 8 KHz.

XII. CONTROLLERS

Fuel cell controller by adjusting amount of input hydrogen and oxygen controls fuel cell voltage. Limiters use in output of any controller to limit the gas pressure in the fuel cell. For determine PID opened loop parameters use of relay auto tuning method.

XIII. CIRCUIT PROFILE

According to Figure 14, this machine has two step motors with Gearbox 100rpm-Transformer 5v- Two DC motors with 1000 rpm- Processor Atmega32- Buffer 74HC240- LM324- Regulator 7805- Atting 26L - OPTOR COUNTER - Atting 45 - Two Mosfets - Display 16 x 2 and 2 x IRF540 power circuit consists of two resistors forming 5W 12V switching power circuit includes a wireless antenna module HMTRP 915 MHz and 915 MHz, respectively.

Four pins for the output signals from the left side include.

A. Ground (GND)
B. Signal transformers (for reference)
C. The first motor signal
D. Two engine signals

In fact, the shape of the output waveform output motors are close to the reference waveform. However, in the circuit for the circuit to be tested at different loads separately came with two motors we circulating axes.

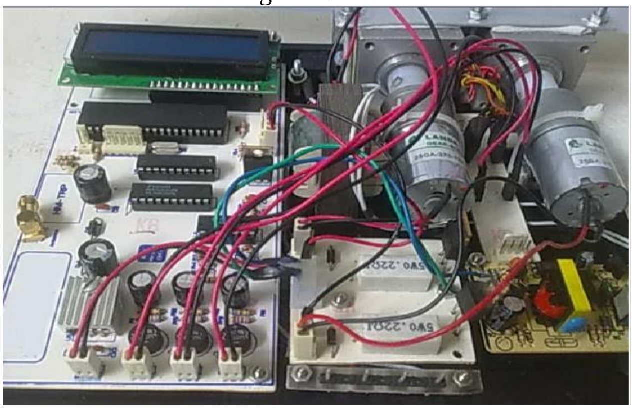

Figure 17. Synchronizer digital devices for both motors

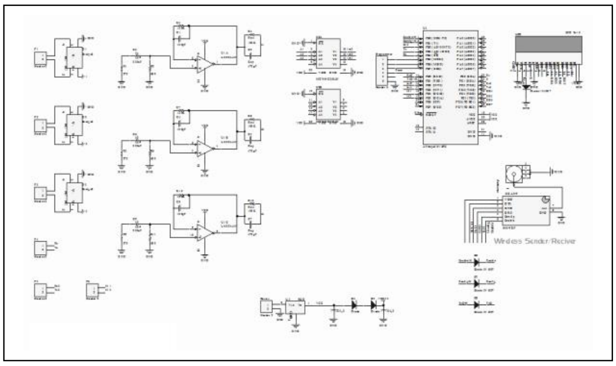

Figure 18 Schematic design of digital Synchronizer

XIV. FULL DESCRIPTION OF THE CIRCUIT

This circuit has three input channels that are registered in the analog wave and full-wave rectified by the diode bridge and then it is taken by three capacitors for dc input value and input of amplifier is LM324 series. This circuit has three input channels that are registered in the analog wave and full-wave rectified by the diode bridge and then it is taken by three capacitors for dc input value and input of amplifier is LM324 series. The amplitude of the square wave output is low which will be increased by buffer 74HC240 to the amplitude in the range of 4 to 4.5 volts. Of course, for getting the exact logical one or the same 5 volts, Atting26L is used within the circuit. This is like the OP AMP which has the amplitude in the range of 4 to 4.5 volts by 3 ADC inputs and the output becomes logical 0 and 1 and its output is connected to the three inputs of Intropt2, Intropt1 and Intropt0 from Atmega32 processor. Then the frequency of each input line is measured in the processor and is shown on the display. In this circuit, the speed of motor is controlled by PWM wave signals from the processor. According to the measurements and formulas in the program and two outputs, if the frequency is more or less than the reference value which is the output of transformer, PWM wave will be amplified by use of two MOSFETs with 12 volts and goes to the input leg of DC motors to change the speed. With the changing speed of the two DC motors as actuators, speed of AC motors in the output as generators is changed through two gearboxs and the output of these generators will finally be close to the reference value.

HMTRP 915 MHz wireless module is also used in this system which sends the desired data by a 915 MHz antenna to the monitoring and without noise system so that we will not be forced to stay close to the generator for reading the measured output. There are four outputs on the bread board for the oscilloscope probes which are from the Left to right as follows, respectively.

Four pins for the output signals from the left side include.

A. GND
B. Reference signal (output of the power transformer
C. Signal output from the first AC motor
D. Signal output from the second AC motor

In reality, the output waveform of motors is usually close to the reference waveform. However, for testing this circuit at different loads, the circulating axes of two motors were controlled separately and manually.

And in this case, using the signal from the processor engine torque, the speed is much enough to be close to the reference waveform or frequency and two LEDs are used to show the electricity in the output.

In this circuit, two ICs are used to measure the speed of the Atting 45 which can measure the speed separately by OPTOR COUNTER which can be used for special cases and is not used in this circuit due to producing noise. There is 12 volt switching power supply on the right side of the circuit.

XV. OUTPUT RESPONSE

According to the output of the circuit in Figure 15, the circuit response is shown on the LCD display when it begins to start which shows power frequency in the right side and frequencies of two motor with the speeds in the left side. The frequency difference of 1 Hz is shown at the beginning.

In Figure 16 which shows the response of the circuit after few milliseconds, synchronizer makes no difference in the frequency and three frequencies are equal. In Figure 17 which the output response of the synchronous waves generated by a square-wave reference that shows different periodic orbits in 1 millisecond is displayed on the oscilloscope screen which from top to bottom in this figure are

A. AC signal (reference)
B. Motors first or second signal, respectively.

Changing in the the output frequency from the beginning is shown in figure 19 and the output of digital synchronizer test from starting time of act is shown in figure 20.

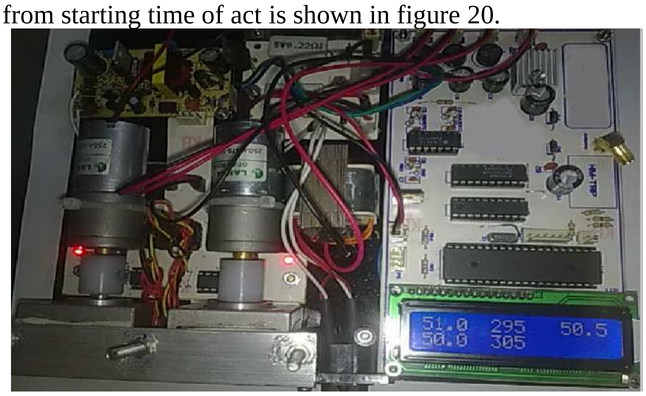

Figure 19 at the beginning of frequencies between 1 Hz

Figure 20 Frequencies between 0 Hz

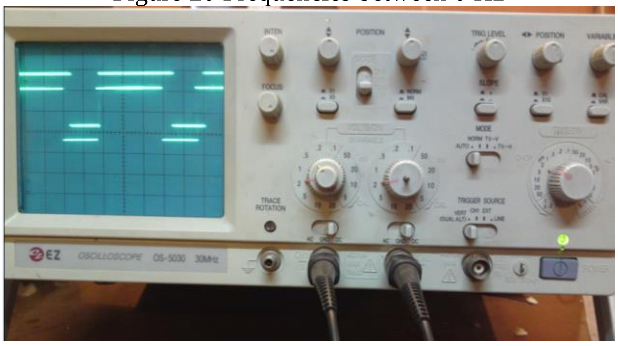

Figure 21 Output waveform on the oscilloscope.

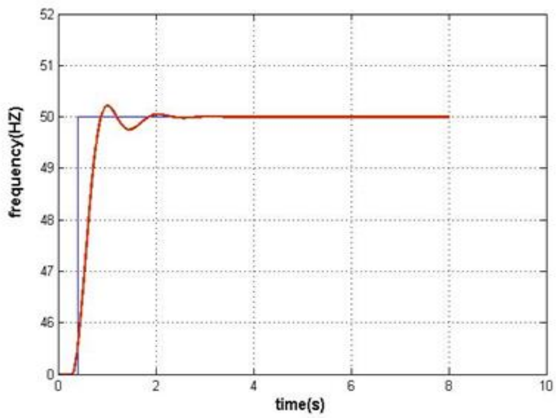

Figure 22 Digital output synchronous practical test

XVI. CONCLUSION

In this paper, a fuel cell power plant was designed in a novel and experimental approach. According to presented approach there was no need to consider the time of connection to the network and the output fluctuation became zero. There was also built an experimental example of digital synchronizer which was efficient in synchronizing distributed generation systems. Based on the output diagram obtained from relay auto tuning algorithm, synchronous time has been reached to less than 2 seconds and also there was no fluctuation in output of stable state and the output become zero in less than 3 seconds. Since in fuel cell system and similar cases, DC/DC and DC/AC convertor with induction circuits have been used inevitably, it was possible to minimize unwanted difference phases from ordinary PID controller by use of relay control system and finally the output was better and more stable. Benefits of distributed generation resources and the parallelism of the PLL and the simplicity of its design, economy of expression and corporations of power generation have been also stated.

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An experimental example of digital synchronizer was also explained completely which worked efficiently.

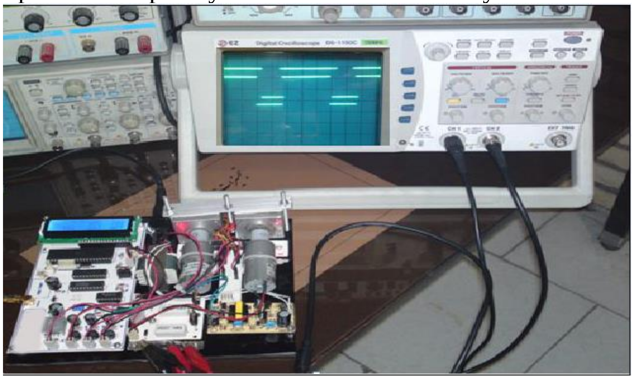

Figure 23 digital outputs Synchronizer practical test

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