

Virtual Synchronoscope for Connecting Synchronous Generator on the Grid

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Abstract — In this paper is presented in a constructive and functional way an instrument that can be used at connecting synchronous generators at the grid supply that has a constant voltage and frequency. Actually it is about a virtual synchronoscope that verifies the correct instant for the synchronization: phase sequence of the generator must be same with the grid, the generator frequency must be equal to the grid frequency, the generator voltages should be equal to the corresponding grid voltages and the generator voltages should be in phase with the corresponding grid voltages. After the conditions of synchronization between synchronous generator and large power grid are occur, the parallel operation of generator is realized automatically. The virtual synchronoscope is designed from two principal components: hardware (LEM's transducer for measurement six voltages, supply voltage, elements for input/output signals conditioning, USB multifunction I/O module) and software (virtual instrument). The main objective of this paper is to create an easy to use device for the study of network synchronization synchronous generators. The LabVIEW graphical programming environment is used for designing virtual instrument. The monitored parameters values are displayed using digital indicators. The real-time voltage waveforms for grid and generator are displayed. With three-phase voltage phasors (voltage vectors) we can see the evolution of phase angles and voltages amplitude. This virtual synchronoscope can be used in engineering education from universities or in testing laboratories of electrical machines.

Keywords: synchronization of synchronous generators; three-phase voltage phasors; virtual synchronoscope.

I. INTRODUCTION

As it is known synchronous machines are used mainly as alternative current generators being called synchronous generators. The synchronous generators are usually operated in parallel and number of parallel generators in an interconnected power system can be as high as hundreds. The principal purpose of this interconnection is the continuity of the service and the economy in plant investment and the operating cost.

To connect a synchronous generator to the grid or parallel operation in several synchronous generators must meet simultaneously a number of technical and operational conditions. [1], [2], [3], [4], [7]

A synchronous generator can be connected to a large power grid that has a constant voltage and frequency by driving it at synchronous speed and adjusting its field current so that its terminal voltage is equal to that of the power grid (or the bus).

In addition, if the frequency of the incoming generator is not exactly equal that of the grid, the phase relation between its voltage and the grid voltage will vary at a frequency equal to the difference between the frequencies of the two voltages.

II. THEORETICAL ASPECTS

Following are some theoretical elements that were the basis for realization proposed virtual instrument. For the design of this instrument are used technical concepts and elements of standardization (IEEE standard of synchronization used for power systems) in the field of electrical machines, data acquisition and virtual instrumentation. [3], [8], [9], [10], [11], [12]

Wiring diagram of a synchronous generator connection to the grid is shown in the figure below.

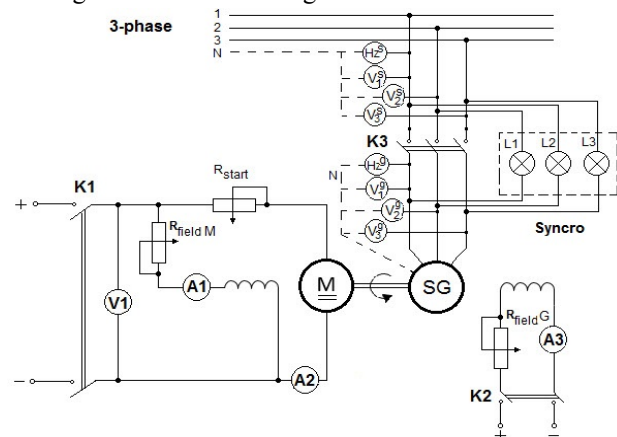


Fig. 1. Wiring diagram for synchronous generator connection to the grid

Voltmeters $V_1^S \dots V_3^S$ are used to measure the phase's voltages of the grid ($V_{S1} \dots V_{S3}$) and $V_1^G \dots V_3^G$ measuring the corresponding generator's phase voltages ($V_{g1} \dots V_{g3}$). The generator or grid frequencies are measured with H_z .

There are more conditions that should be met before the generator is connected to the grid. All of these conditions are named "synchronization".

The procedures for the connecting generator to the grid and synchronization are listed below:

- ensure that the three-phase switch **K3** connected into circuit between the synchronous generator terminals and the infinite bus terminals is in the open position;
- run the DC motor (close the switch **K1**) and adjust the speed so that the synchronous generator frequency is close to the grid frequency;

- after the switch **K2** is closed, adjust the excitation of the synchronous generator ($R_{field}G$) so that the generator voltage is equal to the grid voltage;

- observe with the classical synchroscope (consists of lamps **L1**, **L2** and **L3**) the phase angle between the phase voltage of the generator and the grid voltage. [6]

The correct instant for the synchronization occurs when the following conditions are met simultaneously:

-phase sequence of the generator must be same with the grid; this means that the *Phase 1* of the generator should be connected to *Phase 1* of the grid, *Phase 2* of the generator should be connected to *Phase 2* of the grid and *Phase 3* of the generator should be connected to *Phase 3* of the grid;

-the generator frequency must be equal to the grid frequency; in a balanced three-phase system, this condition can be observed by measuring the frequency of say *Phase 1* voltages on generator and grid sides;

-the generator voltages should be equal to the corresponding grid voltages; this means that the *Phase 1* voltage of the generator should be equal to *Phase 1* voltage of the grid, *Phase 2* voltage of the generator should be equal to *Phase 2* voltage of the grid and *Phase 3* voltage of the generator should be equal to *Phase 3* voltage of the grid;

-the generator voltages should be in phase with the corresponding grid voltages.

At the instant of synchronization, when all of the four conditions listed above are met, switch **K3** can be closed and the generator is connecting to the three-phase system.

The virtual synchroscope consists of a hardware component (Laptop; NI-USB 6259 Data Acquisition Module; LEM Transducers for six voltages; ± 15 Vdc power supply; connectors) and the software component (NI-DAQmx for USB Devices and the designed Virtual Instrument in LabVIEW).

III. HARDWARE COMPONENT

The experimental block diagram of the synchroscope is presented in Fig. 2.

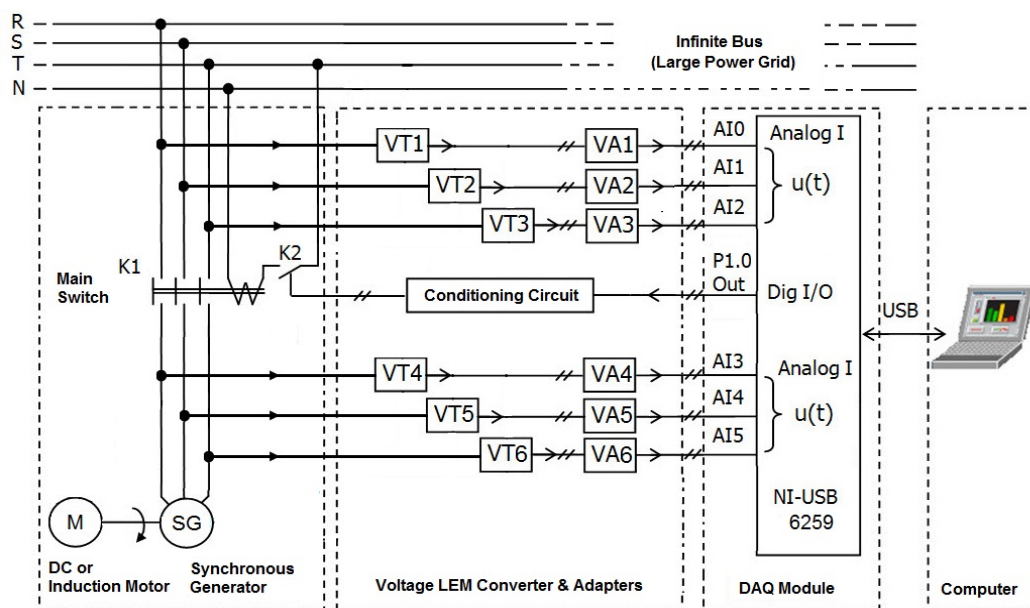


Fig. 2. The experimental schematic block diagram for synchroscope

The main components of block diagram are: unit under test (synchronous generator) with connection/unconnection at the large power grid (three phase contactor **K1**); transducers (VT1...VT6) and adapters' module (VA1...VA6); DAQ module and computer.

As shown in the figure, only six parameters, the grid voltages (V1...V3) and the generator voltages (V4...V6) should be measured in real-time.

The devices used in this experiment have the following features: [11], [12]

Data acquisition module: type NI-USB 6259 with:

-32 analog inputs AI (16 differential and 32 single ended) with 16-bits ADC resolution;

-absolute accuracy for nominal range (± 5 V) is $1,01\mu\text{V}$;

-1.25 MS/s sampling frequency for single channel maximum;

-1 MS/s sampling frequency for multichannel maximum;

-48 multifunction digital inputs/outputs DIO.

Transducers: type PBT LV 25-P, non-inductive transducers LEM provide galvanic isolation, a fidelity measuring for voltages (500 V) and excellent overall accuracy (0,8%). All LEM transducers are powered by a dual source voltage with ± 15 V relative to GND.

Signal conditioning: blocks VA are adapting and conditioning circuits for voltages measured with transducers. The measured values are applied to six analog inputs of DAQ module (AI0...AI5).

The additional signal conditioning circuit is required to interface the main switch with the digital output of the DAQ module. This conditioning circuit containing a integrated opto-coupler (type 4N25) and a inductive relay at 12 V. When the digital output signal P1.0 of the DAQ module is High level (5V), the contact of the relay **K2** is closed and the contacts of three-phase contactor **K1** are also closed. The LED shown when generator is connected on the grid. The digital conditioning circuit is presented in Fig. 3.

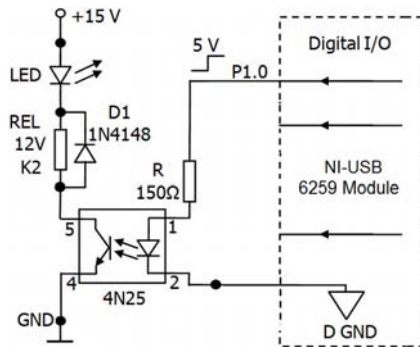


Fig. 3. The conditioning circuit for digital output signal

Synchronous generator: rated power ($P_N=1.5\text{kW}$); rated current ($I_N=3.8\text{A}$); rated speed ($n_N=1500\text{rpm}$).

IV. SOFTWARE COMPONENT

NI-DAQ driver software is an extensive library of functions and virtual instruments by which we can call from LabVIEW to program all the features of 6259 acquisition module.

The proposed Virtual Instrument (VI) was realized using LabVIEW (v. 8.5) and is formed by the user interface (Front Panel) which are composed by graphical objects like numerical buttons and indicators, graphs and the code using VIs to control this front panel objects (Block Diagram). [7], [8]

A. Front Panel

Fig. 4 illustrates the Front Panel of designed Virtual Instrument.

In the left side of the Front Panel we can find the controls for setting input and output parameters. In the right side there are the numerical and graphic indicators.

Also, the seven conditions for synchronization are visual displayed; when all seven are ON (green color) then the MAIN SWITCH is ON and the generator is connected at the grid.

Fig. 5 shows the virtual instrument controls:

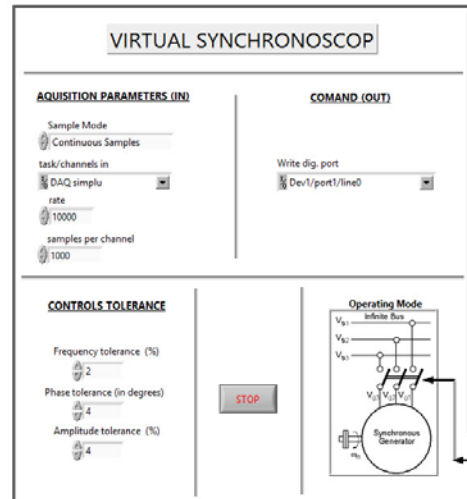


Fig. 5. Controls of Virtual Instrument

-for setting acquisition's configuration: name of task/input channels, sample mode, rate and samples per channel;

-for create channel to generate digital output signal (specifies the names of the digital lines or ports to use to create virtual channels): Write digital port;

-for the calculation of: frequency tolerance (%), phase tolerance (in degrees), amplitude tolerance (%).

To calculate the percentage frequency tolerance ($f_s - f_g$), frequency of the grid (f_s) is selected as frequency reference signal.

$$f_s - f_g = \frac{f_s - f_g}{f_s} \cdot 100 \quad (1)$$

As well as in the other two cases the reference signals are the grid phase and the amplitude of the grid voltage.

In both cases we can determine whether parameter measured (*phase angle* or *frequency*) falls within a range specified by the upper limit and lower limit inputs.

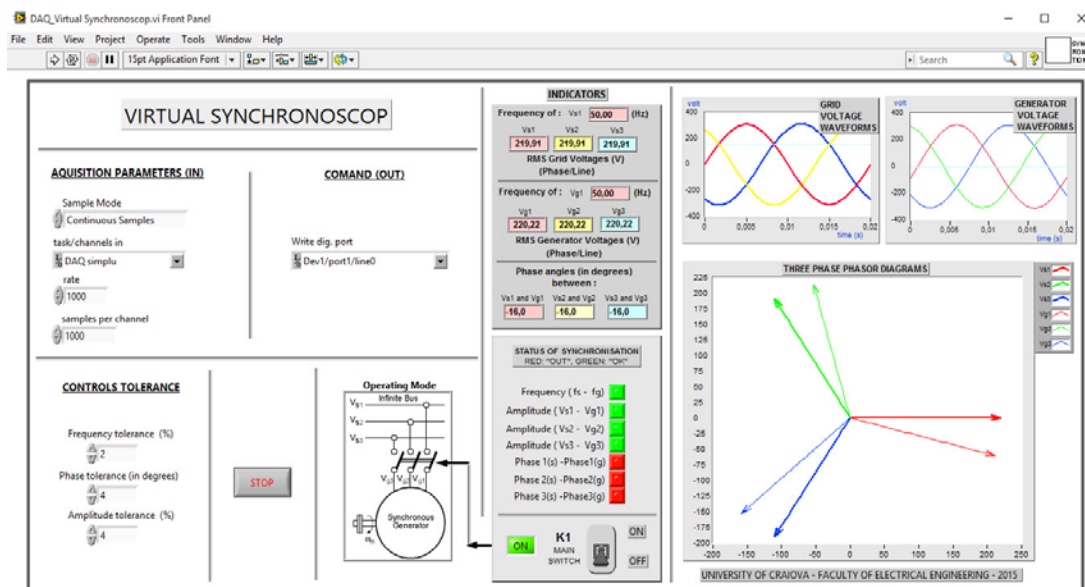


Fig. 4. Front Panel of Virtual Instrument

The numerical indicators are presented in Fig. 6.

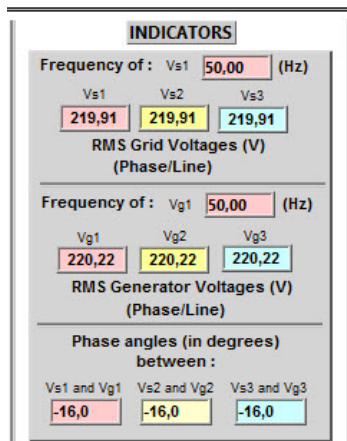


Fig. 6. Numerical Indicators

Numerical values of the frequencies (in Hz) of the grid voltage and generator voltage, phase angles (in degrees) between grid voltage and generator voltage, root mean square values (in volt) of the grid and the generator voltages are calculated and indicated in the figure above.

However, the phase differences of each phase are checked separately (Phase V_1^S and V_1^G ; Phase V_2^S and V_2^G ; Phase V_3^S and V_3^G) to prevent “wrong” connection (wrong phase sequence).

Fig. 7 shows (below) graphic representations for three-phase voltage generator and network waveforms. One graph displays the three-phase supply (grid) voltages. The voltage data is updated regularly. Another graph displays the three-phase generator voltages. The voltage data is updated simultaneously with the grid voltage data.

The three-phase grid (supply) and the generator voltage phasors are displayed in “*Three-phase phasor diagrams*” graph (at the bottom of Fig. 7). Refer to the legend of the graph to determine the corresponding supply and the generator voltage phasors ($V_{S1...S3}$, $V_{G1...G3}$). In the phasor diagram the generator voltage phasor is rotated clockwise by angle ϕ to the grid voltage (generator lags grid). [5]

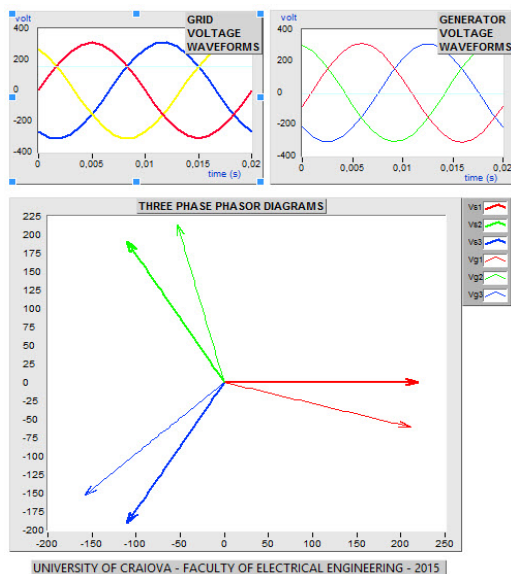


Fig. 7. Graphical Indicators

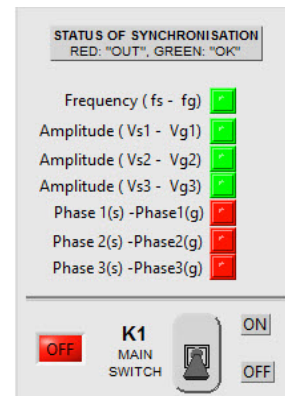


Fig. 8. Visual Indicators of Synchronization

The current status of each of the synchronization condition is displayed in the Fig. 8 by the 7 LED indicators:

- first LED indicate equality of frequency ($f_s - f_g$) with specified tolerance, in percent (i.e. 2%);
- next three LEDs indicates equality of voltages phase with specified tolerance (i.e. 4%);
- last three LEDs indicates equality of the phase differences of each phase with specified tolerance, in degrees (i.e. ± 4 degrees).

At the instant of the "synchronization", all LEDs become GREEN and the main switch K1 changes the position to ON (LED indicator become GREEN – ON).

B. Block Diagram

The Block Diagram contains the graphical source code for how the virtual instrument runs.

Fig. 9 shows the integral's Block Diagram of the virtual instrument for studying of connecting synchronous generator on the network.

As shown in figure, all of elements of the code are included in a repetitive structure (type While Loop), which executed them till now at the finishing terminal (left side, the “Stop if True” state) arrives logical values True. The While Loop always executes at least once. The conditional terminal evaluates a Boolean input value to determine whether to continue executing the While Loop. Before the conditional terminal we use the Compound Arithmetic function to perform an OR operation on three values: first value is from the status of analog acquisition, second value is from the status of digital operation and the last is from the button control STOP.

The **RMS.VI** find the root-mean-square of the input waveforms. The each frequencies of the grid/generator voltages and phase angles between grid and generator voltage are calculated with special four subVIs.

Six instruments (**Draw Vector** subVIs) are used to display the six voltage phasors. Some subVIs are designed for representation of vectors ($V_{S1...S3}$, $V_{G1...G3}$) in Phasors Diagram.

In these subVIs, we use the notions of analytic geometry such as the distance between two points (knowing it coordinate in Cartesian system) or the equation of a line given by one point and line slope (each point on a plane is determined by a distance from a fixed point and an angle from a given direction). [5]

The XY Graph display multiples plot; each plot in the diagram represents a specific color.

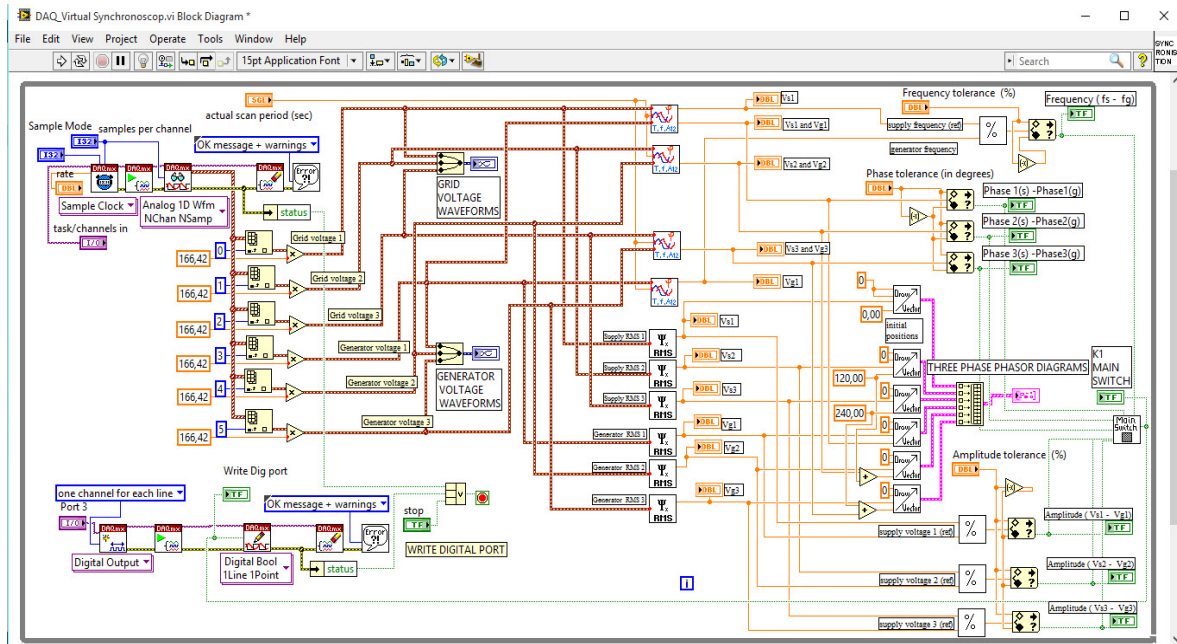


Fig. 9. Block Diagram of Virtual Instrument

We use the next DAQmx – Data Acquisition VIs with hardware module to develop acquisition and control the application:

- DAQmx Timing (Sample Clock).vi;
- DAQmx Start Task.vi;
- DAQmx Read.vi;
- DAQmx Clear Task.vi

The **DAQmx Timing** configures the number of samples to acquire and all timing options.

The **DAQmx Read** properties include additional configuration options for read operations. In this case, we select: Analog – Multiple Channels – Multiple Samples – 1D Waveform.

For automate coupling generator to the grid when the condition of synchronization are stabled is used a digital output signal; the next virtual instruments (VIs) are used for this :

- DAQmx Create Channel.vi;
- DAQmx Start Task.vi;
- DAQmx Write.vi;
- DAQmx Clear Task.vi

The **DAQmx Create Channel** creates channel to generate a digital signal for command a contact K2 of connection relay (see Fig. 3, the conditioning circuit for digital output signal and Fig. 2, the experimental schematic block diagram for synchronoscope).

With the virtual instrument **DAQmx Write** we can write a single Boolean sample to a task that contains a digital output channel composed of a single line; the options for write operations are: Digital – Single Channel – Single Sample – Boolean (1 line).

The phase angle between two voltages is determinate with a subVI block in degree, over a running window of the one cycle of the fundamental frequency (50 Hz, 20 mS).

This subVI is based on the principle of detected peaks or valley of the two input signals (generator or grid voltages).

The *phase* result with formula (2) in degrees:

$$Phase = \frac{t_2 - t_1}{T} \cdot 360^\circ \quad (2)$$

where T is the period of voltage, t_1 is the time moment for first peak (max) of signal 1 (grid/supply voltage 1, V_{s1}), t_2 is the time moment for first peak of signal 2 (generator voltage 1, V_{g1}).

For calculation the frequency of grid/generator's voltage and the phase between voltages design a subVI named f-T-phase.vi. The Block Diagram of this subVI is presented in Fig. 10.

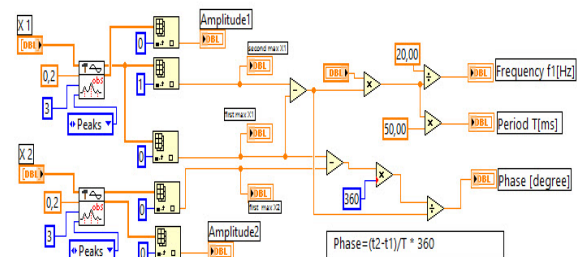


Fig. 10. Block Diagram of Virtual Instrument

The principal element of this subVI is a **Peak Detector VI** what finds the location in time, amplitude and second derivative of peaks or valleys in the specified signal (input voltage). [6]

We use the actual scan period (with a value of 20 mS) for calculation the frequency of grid and generator voltages; frequency result in Hz and phase in degree.

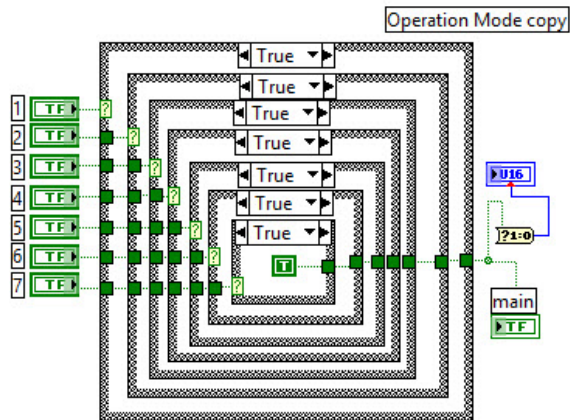


Fig. 11. Block Diagram of Main Switch subVI

The **Main Switch** subVI is used to mark the synchronization status and contains seven sub diagrams type *Case Structure*. This diagram is shown in Fig. 11.

The Case Structure contains one or more sub diagrams, exactly one of which executes when the structure executes. The value wired to the selector terminal determines which case to execute.

The output signal of Main Switch subVI signaled by an LED indicator (OFF – red color; ON – green color) and animates the ring picture in **Operating Modes**: open switch - OFF or close switch - ON (see also Fig. 8).

Virtual instrument run continuously until the STOP button is pressed or until an error on acquisition at analog input or at the digital output. These three sizes in the form of Boolean commands are applied to a logical function ON.

V. FINAL CONSIDERATIONS AND CONCLUSIONS

The main objective of this paper is to create an easy to use device for the study and analyze the stages of synchronization synchronous generators with the large power grid.

This virtual synchronoscope is designed to be used in electrical engineering education or in electrical machines tests.

Because the input voltages from generator and grid can be as high voltage, make sure that this high voltages are correct attenuated and isolated.

The procedure for the synchronization with proposed virtual synchronoscope are summary describes:

- ensure that the MAIN SWITCH (three-phase switch) is in the open position;

- launch the LabVIEW program and run the virtual instrument DAQ_Virtual Synchronoscope;

- choose the values of data acquisition: name of task/input channels, sample mode, rate and samples per channel;

- choose the accepted tolerance for the frequency, amplitude and phase between grid and generator voltages;

- create channel to generate digital output signal for connecting generator to the grid;

- run the DC or Induction Motor and adjust the speed so that the frequency of generator is equal to the grid frequency;

- adjust the excitation of the synchronous generator so that the generator voltage is equal to the grid voltage;

- observe numerical indicators and graphical displays and compare the values obtained with those expected;

- observe the phase angle between the three-phase voltage vectors of the generator and the grid with phasor diagram (see Fig. 7); the phase angle can be observed visually by looking at difference between the identical colour phasor on the graph; the three-phase phasors rotate slowly clockwise or counterclockwise;

- at the end of synchronization operation, when all of the conditions are met, all the seven corresponding LED lights on the panel become green and the MAIN SWITCH change the position to ON and the generator it is automatically connected to the grid.

After using this virtual instrument, students should be able to understand the concept of synchronization and the requirements for the synchronization of a three-phase synchronous generator.

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