Section 1: INTRODUCTION

Understanding concepts such as power factor, harmonics, and Total Harmonic Distortion (THD) is often challenging for beginners in power systems engineering. These parameters play a critical role in determining power quality and overall power consumption. This paper aims to simplify these complex topics by presenting them from a beginner-friendly perspective, bridging the gap between theoretical learning and practical understanding. Traditional power systems textbooks often overwhelm students with excessive detail, making it difficult to grasp the core principles. To address this, the paper provides concise explanations and focuses on visualization-based learning.

A three-phase power system has been simulated using LabVIEW 2015 to demonstrate the impact of harmonics and phase shifts on key parameters such as real power, apparent power, and instantaneous power. The simulation allows users to introduce harmonics and phase shifts in voltage or current waveforms, enabling interactive observation of their effects on power system behavior. Additionally, model calculations are presented to strengthen students' analytical skills and reinforce theoretical concepts.

Recognizing the limitations of conventional textbook approaches that rely solely on fundamental frequency components, this work also emphasizes accurate power calculation methods for non-sinusoidal signals. A LabVIEW-based program has been developed for computing real and apparent power in distorted waveforms, and the complete implementation process is documented to support student learning and replication. This paper thus serves as both a conceptual primer and a practical guide for students beginning their journey in power systems analysis.

Section – 2: HARMONICS - ITS CAUSES AND EFFECTS

Harmonics are sinusoidal waves whose frequency is an integer multiple of the fundamental frequency. No signal is perfectly sinusoidal (Perfectly sinusoidal signal contains only fundamental frequency components). A real-world signal can be said to have the fundamental frequency component as well as many harmonics superimposed together with the fundamental frequency component.

In a generalised way, let $v(t)$ be a voltage signal. It contains the fundamental frequency component $V_1 \sin sin\,(2\pi ft)$ as well as harmonics.

$$v(t) = V_1 \sin sin\left(2\pi ft + \varphi_1\right) + V_2 \sin sin\left(4\pi ft + \varphi_2\right) + ... + V_n \sin sin\left(2\pi nft + \varphi_n\right)$$

Where,

V_1 = magnitude of the fundamental voltage.

w_1 = fundamental angular frequency (in radians) ($w = 2\pi f$)

f_1 = fundamental frequency (in Hz)

V_n = magnitude of n^{th} order harmonics.

φ_n = Phase shift of n^{th} order harmonics

2.1. Causes of Harmonics:

Harmonics are produced by non-linear loads. Some of the common non-linear loads are listed below.

a. Electronic Ballasts in lighting
b. Speed-control drives for air-conditioning and elevators
c. Switching mode power supplies (SMPS)
d. Computers and desktops
e. Power electronic converters and inverters.
f. Transformers and motors whose core are saturated.

2.2. Effects of harmonics:

- The presence of harmonics causes an increase in the I_{RMS} and hence the resistive losses ($P_{loss} = I_{rms}^2 * R$) increases in the transmission lines / underground cables.

- Harmonics of higher orders can cause interference in telecommunication lines.

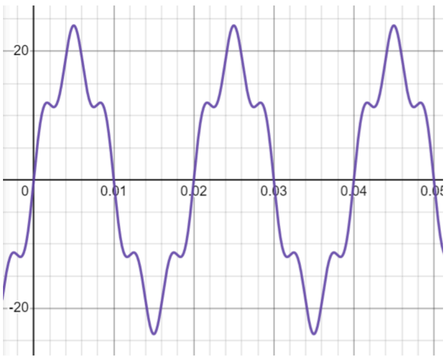
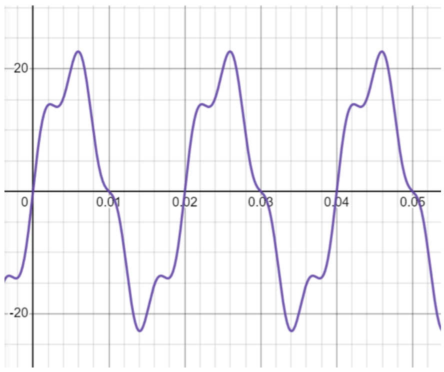
- Eddy current losses in transformer core are proportional to the frequency ($P_{eddy} \alpha f^2$) of input voltage. Hence if the input contains harmonics, eddy current losses will be increased.

- Harmonics can cause excess heating, vibration and humming noise in transformers and motors.

2.3. Types of harmonics:

1) Even harmonics
2) Odd Harmonics

In an electrical power system, odd harmonics are more dominant. The differences between even and odd harmonics are tabulated in the table below.

	Odd Harmonics	**Even Harmonics**
1	The harmonics where n is an odd number strictly greater than 1 (n = 3, 5, 7, 9, …)	The harmonics where n is a non-zero even number. (n = 2, 4, 6, 8, …)
2	Example: 5th order harmonics is present  $v(t) = 20sin(100\pi t) + 4 \sin sin\ (500\pi t$	Example: 4th order harmonics is present  $v(t) = 20sin(100\pi t) + 4 \sin sin\ (40$
3.	Odd harmonics do not remain the same when folding operation is performed. $x(t) = -x(-t)$	Even harmonics remain same when time folding (reversal operation) is performed $x(t) = x(-t)$

Section – 3: DEFINITIONS:

In this section, the important terms that are frequently used are defined using a simple language. There are many terms like apparent power, real power, etc which, at times, are quite confusing.

a. **Instantaneous voltage:**

The value of voltage $v(t)$ at any instant of time t.

$$v(t) = V_1 \sin sin \left(w_1 t + \varphi_1\right) + V_2 \sin sin \left(w_2 t + \varphi_2\right) + \dots + V_n \sin sin \left(w_n t + \varphi_n\right)$$

b. **Instantaneous current:**

The value of current $i(t)$ at any instant of time t

$$i(t) = I_1 \sin sin \left(w_1 t + \varphi_1\right) + I_2 \sin sin \left(w_2 t + \varphi_2\right) + \dots + I_n \sin sin \left(w_n t + \varphi_n\right)$$

c. **Root Mean Square Value:**

The RMS value (also known as effective value) of a periodic current is the dc current that delivers the same average power to a resistor as the periodic current.

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \sqrt{\sum_{k=1}^{\infty} \frac{V_k^2}{2}} = \sqrt{\sum_{k=1}^{\infty} V_{krms}^2}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{\sum_{k=1}^{\infty} \frac{I_k^2}{2}} = \sqrt{\sum_{k=1}^{\infty} I_{krms}^2}$$

- Calculation of power dissipation is an important aspect in AC circuit analysis.
- The calculation will be difficult when current is varying with time period. That is why, RMS value is used. It is a constant value that depicts the time varying current and RMS value yields the same power dissipation.

d. Instantaneous Power:

The electric power at any instant of time is known as instantaneous power. It is measured in **Watts**. The instantaneous power absorbed by an element is the product of instantaneous voltage v(t) across the element and the instantaneous current i(t) through the element.

$$p(t) = v(t) * i(t)$$

e. Real power (P):

It is the average of the instantaneous power over one time period. Average power can also be defined as the power dissipated by the current that is in phase with the voltage. It is also known as the average power.

For a continuous-time signal,

$$P = \frac{1}{T}\int_{0}^{T} v(t)i(t)dt$$

The above equation can be simplified using trigonometric identities as

$$P = \sum_{k=1}^{\infty} V_{krms} I_{krms} \cos cos\left(\theta_{vk} - \theta_{ik}\right) = P_{1avg} + P_{2avg} + \cdots$$

where,

V_{krms} – peak value of k^{th} order voltage harmonic

θ_{vk} – phase shift of k^{th} order harmonic voltage with respect to reference.

θ_{ik} – phase shift of k^{th} order harmonic current with respect to reference.

P_k – product of V_{krms}, I_{krms} and $cos(\theta_{vk} - \theta_{ik})$

f. Reactive Power (Q):

The power which flows back and forth, that is, in both directions in the circuit is called reactive power. It's unit VAR (voltage ampere reactive)

It can also be defined as the power dissipated by the current component that is 90° out of phase with the voltage across the element.

$$Q = \sum_{k=1}^{\infty} V_{krms} * I_{krms} * sin(\theta_{vk} - \theta_{ik})$$

g. **Apparent Power (S):**

It is the product of RMS current and RMS voltage. It can also be defined as the complex sum of real power and reactive power. The unit is VA (Volt Ampere)

$$S = V_{rms} I_{rms}^{*}$$

$$S = P + jQ$$

h. **Power factor:**

It is the ratio of the real power (P) absorbed by the load to the apparent power (S) flowing in the circuit.

$$PF_{total} = \frac{P}{S} = \frac{V_{rms} I_{rms} cos(\theta_v - \theta_i)}{V_{rms} I_{rms}} = cos(\theta_v - \theta_i)$$

$$PF_{total} = PF_{displacement} \times PF_{distortion}$$

The power factor for various types of loads are tabulated below

Type of load	V and I Phasor Relationship	Power Factor $cos(\theta_v - \theta_i)$
Pure Resistive load	Load voltage and load current are in phase ($\theta_v = \theta_i$)	Unity power factor
Pure inductive load	Load current lags load voltage by 90° ($\theta_v = \theta_i + 90°$)	Zero power factor (lagging)
Pure capacitive load	Load current leads load voltage by 90° ($\theta_i = \theta_v + 90°$)	Zero power factor (Leading)

In practical situations, almost all loads are RL loads. Hence it is very important to understand how much power is consumed by the load from the total power supplied. This is why the power factor is significant.

i. **Displacement power factor:**

It is the power factor of the load when only the fundamental frequency components are considered.

$$pf_{displacement} = \frac{P}{V1_{rms}\, I_{1_{rms}}}$$

j. **Distortion Power factor:**

It is the ratio of total power factor to the displacement power factor. It is a parameter which takes the harmonic components present in the circuit into account.

$$PF_{distorsion} = \frac{PF_{total}}{PF_{displacement}}$$

Theoretically, distortion power factor can also be found by using the THD of voltage and THD of current.

$$PF_{distortion} = \frac{1}{\sqrt{1+\left(\frac{THD_V}{100}\right)^2}\sqrt{1+\left(\frac{THD_I}{100}\right)^2}}$$

k. **Total Harmonic Distortion:**

Total harmonic distortion of a sine wave is the ratio of the square root of the sum of magnitudes of all the harmonic components to the magnitude of the fundamental component.

$$THD_V = \frac{\sqrt{\sum_{k=2}^{\infty} V_{krms}^2}}{V_{1rms}} \times 100\%$$

SECTION-4: LabVIEW Software

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a system-design platform and development environment for a visual programming language from National Instruments. LabVIEW integrates the creation of user interfaces (termed front panels) into the development cycle. LabVIEW programs-subroutines are termed virtual instruments (VIs). Each VI has three components: a block diagram, a front panel, and a connector pane.

The graphical approach also allows nonprogrammers to build programs by dragging and dropping virtual representations of lab equipment with which they are already familiar. The LabVIEW programming environment, with the included examples and documentation, makes it simple to create small applications.

LabVIEW includes extensive support for interfacing to devices such as instruments, cameras, and other devices. Users interface to hardware by either writing direct bus commands (USB, GPIB, Serial) or using high-level, device-specific drivers that provide native LabVIEW function nodes for controlling the device.

Section – 5: Developing LabView program for power measurement

Section 5.1: Entire Program

As mentioned in section – 4, LabVIEW is a graphical programming language. Hence a LabVIEW program is an interconnection of many in-built LabVIEW modules, sub-VI and user defined sub-VI.

The figures 5.1 and 5.2 are the LabView Program developed. The ‘plug’ icon in figure 5.1 simulates a voltage/current signal with fundamental frequency component as well as harmonics. The monitor icon in figure 5.2. is a user-defined sub VI that calculates real power, apparent power and power factor.

LabVIEW program (Figure 5.1)

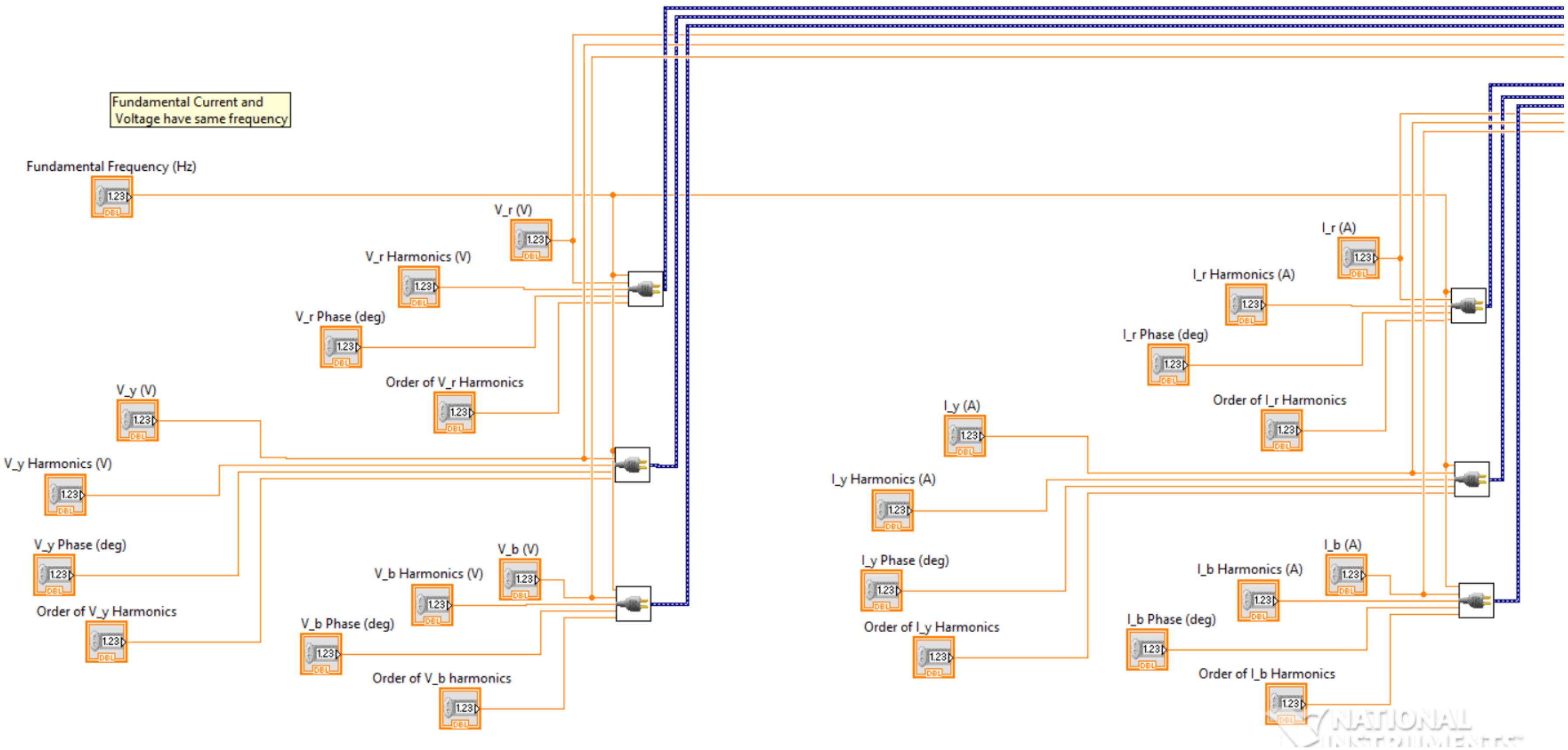
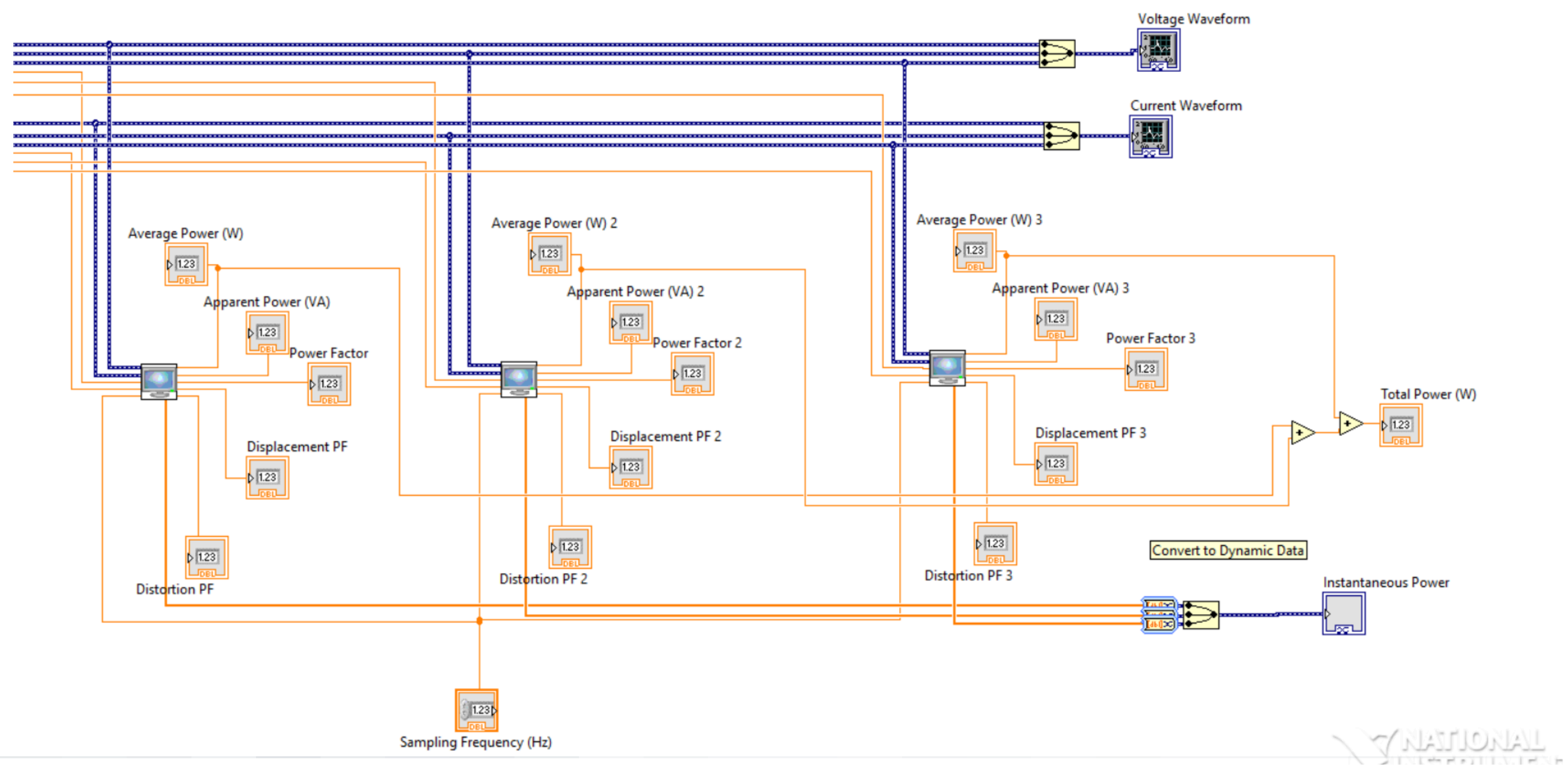


*Figure SEQ Figure * ARABIC 1 LabVIEW Program Part-1 (In this figure, the left half of the program is shown. In this left half, all the voltages and currents in the 3-phase supply are simulated)*

LabVIEW Program Continued (Figure 5.2)



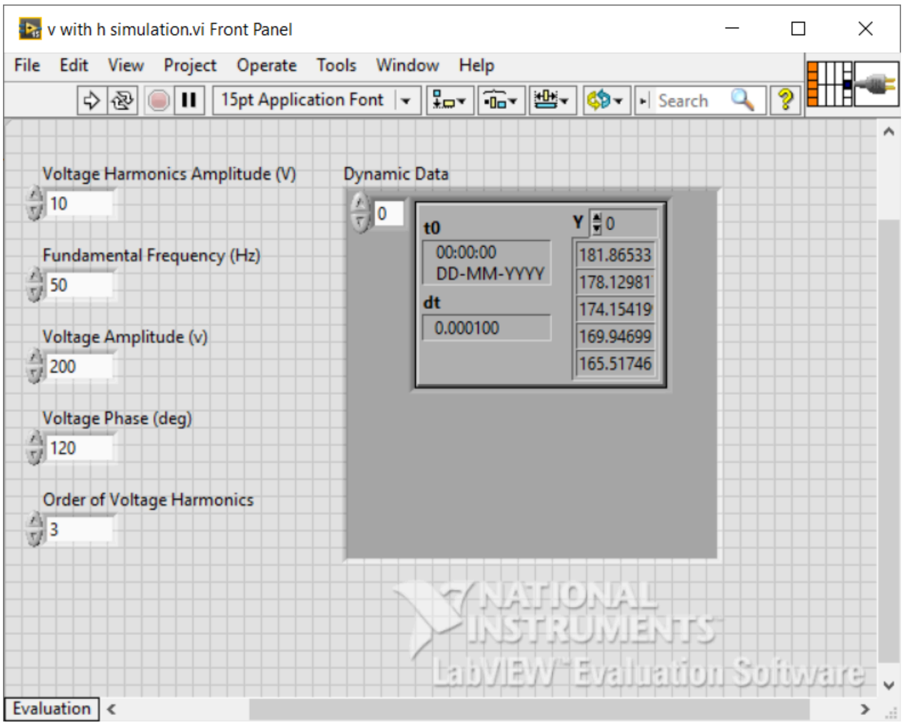
Section 5.2. User-defined Sub VIs

a. Simulating a signal with harmonics

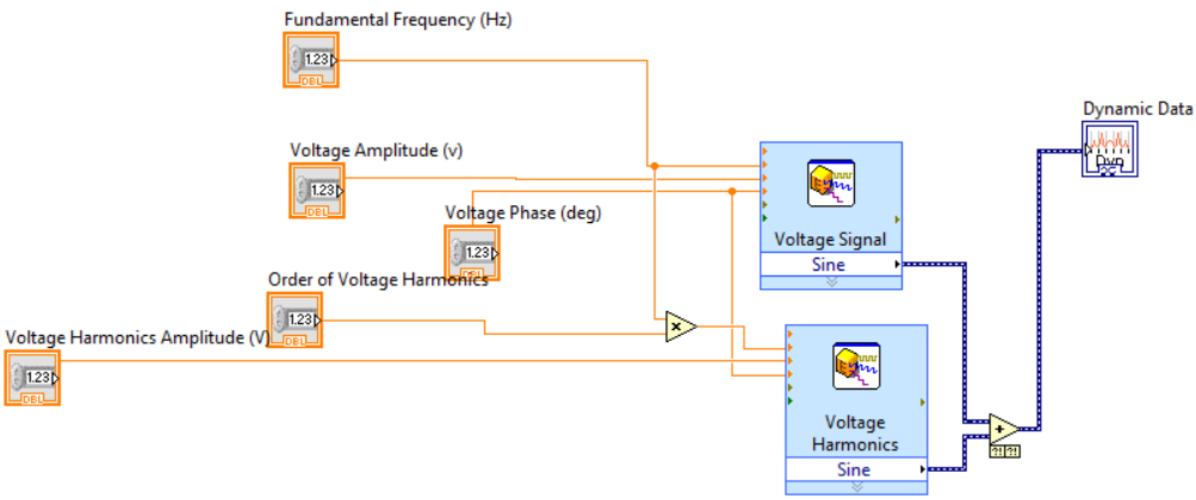
Inputs: Fundamental signal Amplitude, Fundamental frequency, phase of the signal, harmonics signal Amplitude, order of harmonics

Outputs: Signal with harmonics (Dynamic data)

Front Panel of sub VI



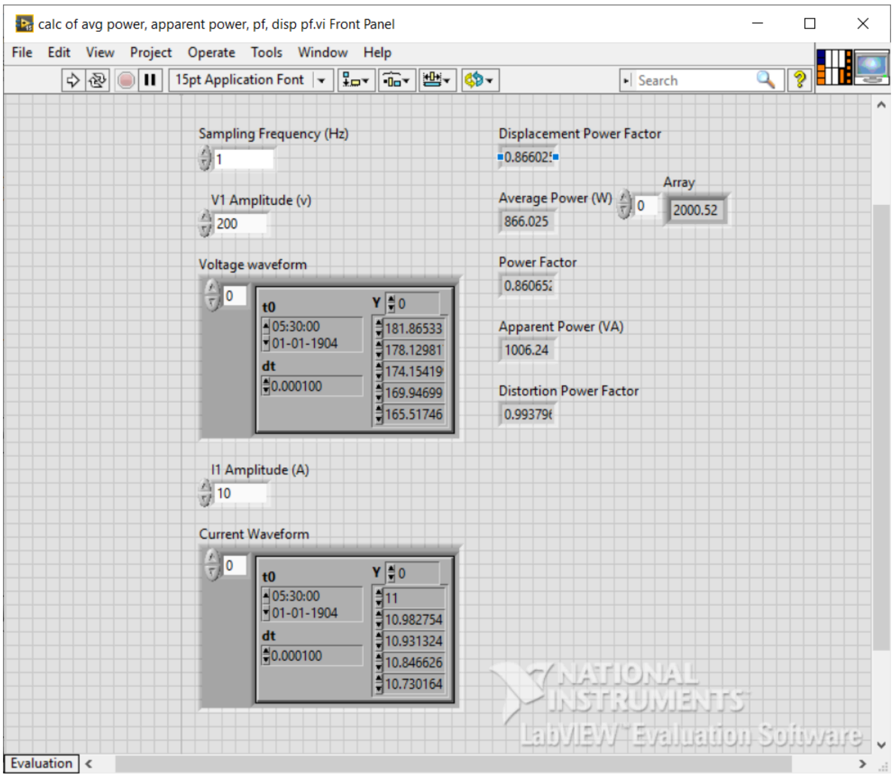
Block diagram of sub VI



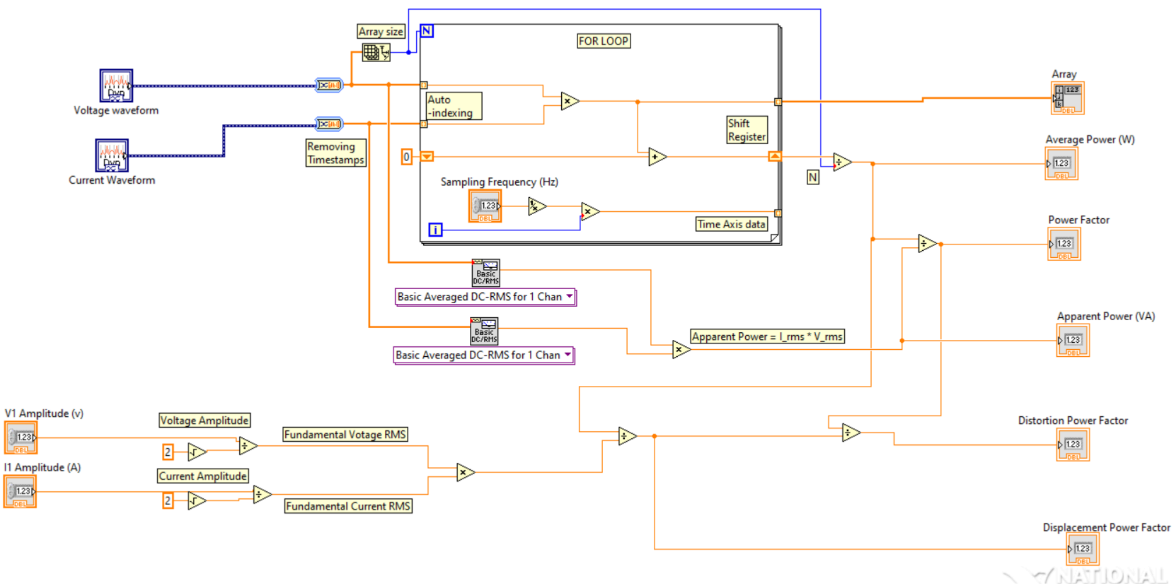
b. SUB VI for calculating average power, apparent power, total power factor, displacement power factor, distortion power factor

Inputs: Current waveform, voltage waveform, magnitude of fundamental current and voltage component and sampling frequency.

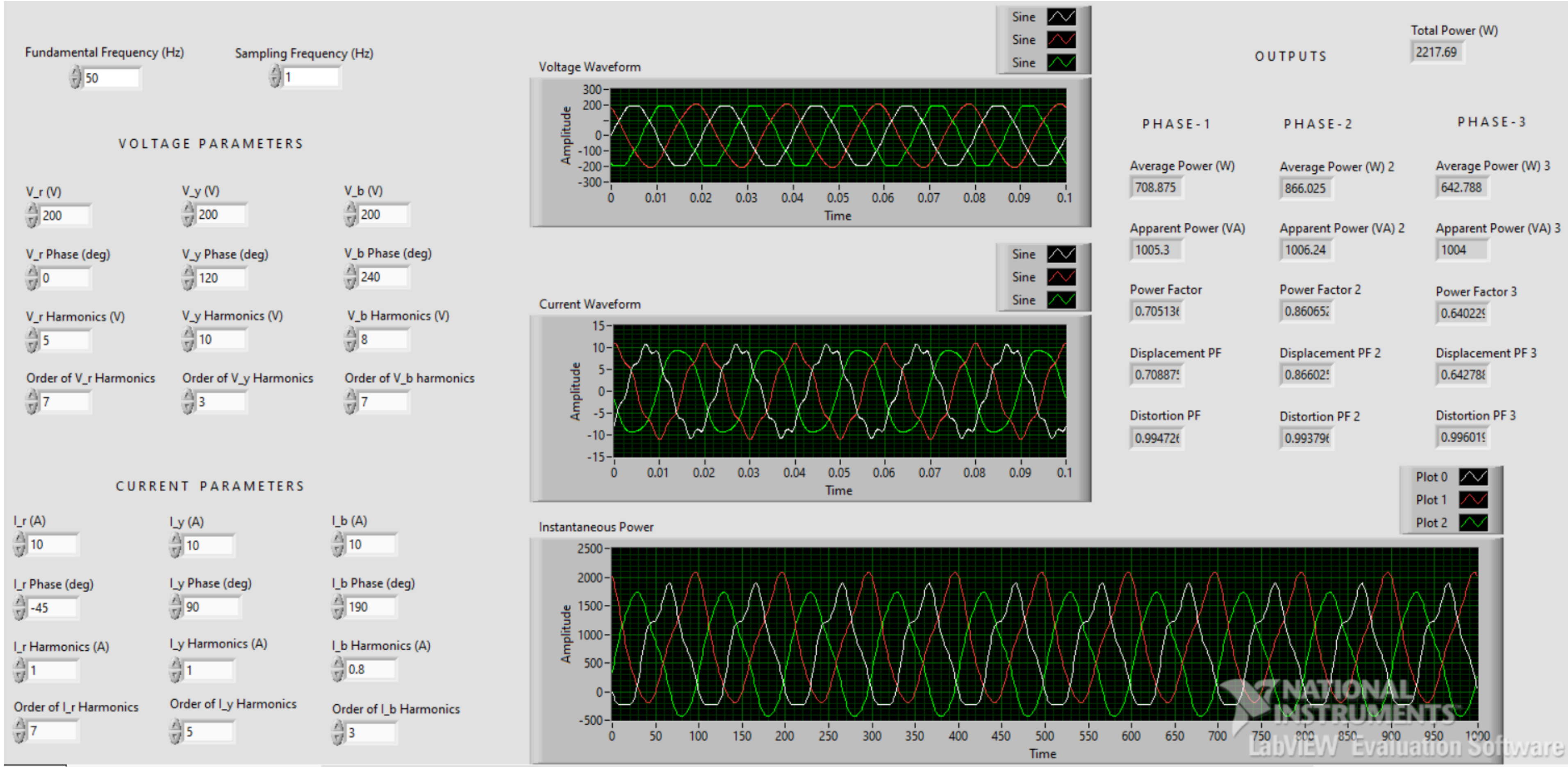
Front Panel of Sub VI



Block Diagram of sub VI



Section 5.3. Output of LabVIEW Program:



Section 5.4. Procedure for LabVIEW program Development

1. **Sub VI for Simulating voltage and Current Signals:**
   In order to measure analyze power and other parameters of a 3-phase supply, voltage and current signals should be fed to the measurement system. Since, DAQ is unavailable, voltage and current signals are simulated in LabVIEW.
   - **i.** To simulate voltage, add two '**Simulate Signal'** blocks (In block diagram panel, Right click □**Express** □ **Input** □ **Simulate Signal**). One Simulate Signal block is for the fundamental voltage signal and the other is for the voltage harmonics.
   - **ii.** Create numerical control for the frequency, amplitude and phase of both the simulate signal blocks.
   - **iii.** Set the frequency for fundamental signal as **50Hz** and set the sampling rate very much higher (say, 10 kHz) since harmonics are also present in the signal.
   - iv. Create a numeric control named '**Order of Harmonics**'. Set the frequency of the harmonics signal block such that the frequency of harmonics will vary accordingly with the order of harmonics, the user has entered.

$$harmonics\ signal\ frequency\ =\ Order\ of\ harmonics\ *\ Fundamental\ Frequency.$$

   - v. Add the fundamental frequency voltage signal and harmonics voltage signal.
   - vi. Now select all the blocks that are employed in simulating voltage with harmonics except the input and output blocks and click **Edit** □ **Create a Sub VI**
   - vii. A new user defined block will be created. Double click on it to open its front panel and block diagram. The pattern of inputs and outputs of the block can be changed and the icon can also be changed.
   - viii. Save the Sub VI file. (File Name: v_with_h_simulation)
   - ix. To use this Sub VI, either copy paste the Sub VI block which is created earlier or in the block diagram window, **right click** □ **Select a VI** and select the Sub VI you saved earlier.
   - x. Using this Sub VI file (v_with_h_simulation), the voltages and currents of 3 phases are simulated.

2. **Displaying the Voltage and Current Waveform:**
   To compare the voltage and current waveforms, the both signals need to be plotted in the same graph.
   - i. Insert the 'Merge Signal' block in the block diagram window (In block diagram, right click □**Express** □**Signal Manipulation** □ **Merge signal**)
   - ii. Give all the 3 voltage signals as inputs to the Merge signal block. Connect the output of Merge signal block to a waveform graph. The waveforms will be displayed.
   - iii. Repeat the above steps for displaying all 3 current waveforms.

3. **Sub VI for Computing average power, apparent power, total power factor, displacement power, distortion power factor**

(a) Calculating instantaneous power

- **i.** Remove the timestamps from the voltage and current signals by using **'Convert from Dynamic Data'** block.
- **ii.** Create a for loop (In block diagram, right click **Programming Structures For loop**).
- **iii.** Using the 'array size' block, set the N value of for loop as the size of either the voltage array or current array. Make sure both current and voltage array have the same number of elements.
- **iv.** Inside the for loop, multiply current and voltage value in each iteration (Auto-indexing is helpful for this process). This is the instantaneous power (array).

(b) Calculating Total Power Factor:

- **i.** In the for loop, add a shift register and set its initial value to zero.
- **ii.** Add all the values of instantaneous power with the **shift register** and divide the total by the total number of values (N). Create an indicator for average power (true power).
- **iii.** To get apparent power, we require the RMS values of current and voltage. So, insert two **Basic DC RMS blocks**, give voltage and current arrays as inputs and find the RMS values of current and voltage RMS.
- **iv.** Now multiply RMS current and RMS voltage to get **apparent power.**
- **v.** To get **true power factor** (or total power factor), divide real power by apparent power.
- **vi.** Display the Total power factor.

(c) Calculating Displacement Power factor

$$PF_{displacement} = \frac{P_{avg}}{V_{1rms} I_{1rms}}$$

- i. To get V_{1rms} (RMS value of fundamental component of voltage signal) and I_{1rms} (RMS value of fundamental component of current signal), the amplitudes of fundamental voltage signal and fundamental current signal should be divided by $\sqrt{2}$.

ii. Divide the true power found earlier by the product of V_{1rms} and I_{1rms} to get the displacement power factor. Display the displacement power factor with a numeric indicator.

iii. To get the **distortion power factor**, divide the total power factor by displacement power factor. Display distortion power factor.

- Now, select all the blocks which are involved in the computation of average power, apparent power, power factors except the input and output blocks and click **Edit Create Sub VI**
- Modify the pattern and icon of the block if needed.
- Save the Sub VI file
- Use the Sub VI file to calculate average power, apparent power, power factors of all the three phases individually.

4. Displaying instantaneous powers in XY graph:

i. Insert a **Merge signal** block (In block diagram, right click **Express Signal Manipulation Merge signal**)

ii. Pass all three instantaneous power arrays from the Sub VI block as input to the Merge signal block

iii. To plot the instantaneous power, time axis data is also required. To obtain time axis data, insert a numeric control inside a "for loop" with the value of sampling rate (Hz). The N value of the for loop is equal to the array size of the voltage/current array (from simulate signal block)

iv. Take the reciprocal of the sampling rate and then multiply it to the control variable (i) of the for loop. Then take this output outside the for loop to get time axis data (array).

v. Create a bundle (In block diagram panel, right click **Programming Cluster Bundle**) with output of merge signal and time axis array. Then plot this bundle with an XY graph. This XY graph is the **instantaneous power graph.**

Section 5.5. MODEL CALCULATIONS:

For R-Phase Voltage and Current)

RMS and THD of Voltage and Current

Known Data:

$V_{fundamental} = 200V; I_{fundamental} = 10A,\ V_{7th\ harmonics} = 5V;$
$I_{7th\ harmonics} = 1A;\ \ Fundamental\ frequency = 50Hz;\ No.\ of\ samples = 1000$

$$V_{fundamental\ RMS} = \frac{V_1}{\sqrt{2}} = \frac{200}{\sqrt{2}} = 141.421V$$

$$V_{Harmonics\ RMS} = \frac{V_7}{\sqrt{2}} = \frac{5}{\sqrt{2}} = 3.53553V$$

$$THD_V = \frac{\sqrt{\sum_{k=2}^{\infty} V_{krms}^2}}{V_{1rms}} \times 100\% = \frac{\sqrt{V_{7rms}^2}}{V_{1rms}} \times 100\% = \frac{\sqrt{5^2}}{200} \times 100\% = 2.5\%$$

$$I_{fundamental\ RMS} = \frac{I_1}{\sqrt{2}} = \frac{10}{\sqrt{2}} = 7.07106A$$

$$I_{Harmonics\ RMS} = \frac{I_7}{\sqrt{2}} = \frac{1}{\sqrt{2}} = 0.707106V$$

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty} I_{krms}^2}}{I_{1rms}} \times 100\% = \frac{\sqrt{I_{7rms}^2}}{V_{1rms}} \times 100\% = \frac{\sqrt{1^2}}{10} \times 100\% = 10\%$$

Real Power and Apparent Power

Known Data:

$V_{fundamental} = 200V; I_{fundamental} = 10A,\ V_{7th\ harmonics} = 5V;$
$I_{7th\ harmonics} = 1A;\ \ Fundamental\ frequency = 50Hz;\ No.\ of\ samples = 1000$

$Phase\ Difference = 45\ deg$

$$Real\ Power = V_{1rms} * I_{1rms} * \cos cos\left(\varphi_1\right) + V_{7rms} * I_{rms} * \cos cos\left(\varphi_2\right)$$

$$= 141.421 * 7.07106 * \cos cos\,(45) + 3.53553 * 0.7071 * \cos cos\,(45)$$

$$= 708.874$$

$$Apparent\ Power\ = V_{rms} * I_{rms}$$

$$= \left(\sqrt{V_{1rms}^2 + V_{2rms}^2 + \ ...\ + V_{n\_rms}^2}\right)\left(\sqrt{I_{1rms}^2 + I_{2rms}^2 + \ ...\ + I_{n\_rms}^2}\right)$$

$$= \left(\sqrt{141.421^2 + 3.53553^2}\right)\left(\sqrt{7.07106^2 + 0.7071^2}\right) = 1005.3015W$$

Total Power Factor, Displacement Power Factor and Distortion Power Factor

Known Data:

$V_{fundamental} = 200V; I_{fundamental} = 10A,\ V_{7th\ harmonics} = 5V;$
$I_{7th\ harmonics} = 1A;\ \ Fundamental\ frequency\ = 50Hz;\ No.\ of\ samples\ = 1000$

$$PF_{true} = \frac{P_{avg}}{V_{rms} I_{rms}}$$

$$PF_{true} = \frac{708.8745}{1005.3015} = 0.70514$$

$$PF_{displacement} = \frac{Real\ Power}{V_{1rms} * I_{1rms}} = \frac{708.8745}{141.421*7.07106} = 0.70888$$

$$PF_{distortion} = \frac{1}{\sqrt{1+\left(\frac{THD_V}{100}\right)^2}\sqrt{1+\left(\frac{THD_I}{100}\right)^2}}$$

$$PF_{distortion} = \frac{1}{\sqrt{1+\left(\frac{2.5}{100}\right)^2}\sqrt{1+\left(\frac{10}{100}\right)^2}}$$

$$= 0.99472$$

Section – 6: Key Takeaways:

- Average power, apparent power, RMS voltage and power factor are independent of the voltage and current frequency.

- Power factor will vary when harmonics are present in voltage and/or current signals.

- When the voltage and current signals are purely sinusoidal, $PF_{distortion} = 1$,

$$Hence, PF_{total} = PF_{displacement}$$

- In real world power factor measurements, **first principles method** is only used, V*I*cos(phi) formula is not used since the phase difference between voltage and current cannot be determined easily.

- When the input signal contains harmonics, the sampling frequency should be set to a higher value.

- **Harmonic distortion analyser** block takes a signal in and performs a full harmonic analysis, including measuring the fundamental frequency tone and harmonics, and returning the fundamental frequency, all harmonic amplitude levels, and the total harmonic distortion.

- The power factor in a single-phase circuit (or balanced three-phase circuit) can be measured with the wattmeter-ammeter-voltmeter method, where the power in watts is divided by the product of measured voltage and current. The power factor of a balanced polyphase circuit is the same as that of any phase. The power factor of an unbalanced polyphase circuit is not uniquely defined.

Section – 7: REFERENCES

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