

# Design a Practical Simulator for Testing Capacitor Banks Panel

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**Abstract**—Power factor correction is needed on the electrical installation in the way to reduce the usage of electrical consumptions. Technology which commonly used to do power factor correction is using several Capacitor Banks with Power Factor Regulator (PFR) module to control them. However, there is a problem for panel makers when they manufacture a Capacitor Banks Panel and need to test it. They need Load Banks with the minimum capacity as same value as Capacitor Banks capacity to make sure that the Capacitor Banks are working well as controlled by their PFR. In this paper, we will design a practical simulator which will be useful for the panel makers do testing the setting of PFR module so it can control the Capacitor Bank to work properly without needing of any Load Banks. The result shows that the prototype is able to be used to simulate the operation of PFR module for controlling 12 steps of Capacitor Bank with different capacity rating by setting the variable resistor on its step.

**Keywords**—power factor, capacitor banks, power factor regulator, simulator.

## I. INTRODUCTION

In the complex electrical installation, such as in the High-Rise Buildings, Commercial Buildings and Factory, power factor becomes an important key to consider by the electrical consultant when designing or auditing a building. Higher power factor means higher efficiency and less electrical consumptions. In the electrical terms, we usually called power factor as  $\cos \phi$  [1], which is calculated by taking the ratio of True Power to Apparent Power as represented by Power Triangle in Fig. 1 below.

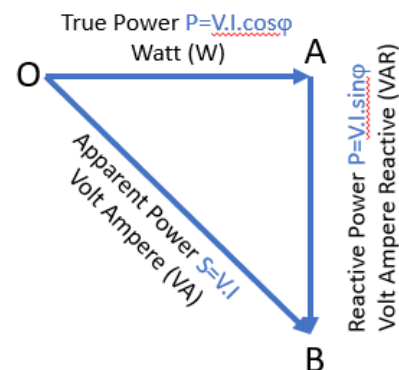


Fig. 1. Power triangle

In Indonesia, there is a rule released by the Ministry of Energy and Mineral Resources no. 9/2011 which stated that minimum power factor must be 0.85. The consequences when the measured power factor in a building is less than 0.85, the building's owner must pay some fines. The amount of the fines depends on the value of KVARh. KVARh can be calculated by crossing the value of Reactive Power and duration of load activated in hours.

The power factor value is related to the type of loads installed in the building. The inductive loads, such as conventional pump, fluorescent tube ballast, machine with inductive motor, transformer, etc. usually have low power factor. Inductive loads have a characteristic that the current wave is left behind the voltage wave by certain phase angle, we called it as lagging power factor. The electrical consultant must apply such solution to power factor correction by installing some series of Capacitor Banks. Capacitor Banks are type of capacitive loads which make the current wave leads the voltage wave by certain phase

angle, we called it as leading power factor [2] as shown in Fig. 2.

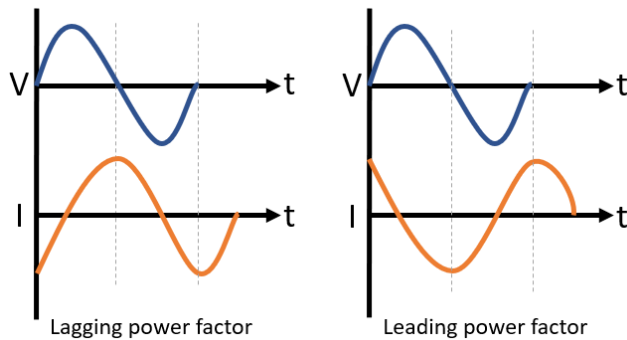


Fig. 2. Lagging and leading power factor

As a solution to do power factor correction, Capacitor Banks need to design properly. Electrical consultant usually designs a series of Capacitor Banks in several steps which can be controlled using Power Factor Regulator (PFR) module in an Electrical Panel. He needs to consider that the power factor in a building will not always at the same value and must be fluctuated. Commonly, the number of Capacitor Banks steps is up to 12 steps. Capacitor Banks Panel is installed in the downstream of Main Distribution Panel (MDP) [3] and in parallel with the loads as shown in the Single Line Diagram (SLD) in Fig. 3. From the SLD which designed by electrical consultant, it is realized by the panel maker becomes a set of Capacitor Banks Panels then installed in the project site. Panel maker must guarantee the quality and function of the Capacitor Banks Panel. They can assure the function by testing, but it becomes problem because they need a Load Banks with minimum capacity as same value as the Capacitor Banks capacity.

As example, to test 100 kVAR Capacitor Banks, they need to provide 100 kW of Load Banks which the rental price is expensive. Other problems come when they need to test a huge capacity of Capacitor Banks Panel. They will not able to do test in their factory due to limited power capacity. Its mean, they have to do testing at the project site after all installation is finished. The question is, how if there is a problem with the Capacitor Banks Panel, such as with its PFR module during testing at the project site? How if the Capacitor Banks Panel urgently needs to be activated and there is no more time to do repairment? Considering the functions and how critical is Capacitor Banks Panel in the electrical installation, we write this paper to propose a design of practical simulator which will be useful for the panel makers do testing the setting of PFR module so it can control the Capacitor Bank to work properly without needing of any Load Banks.

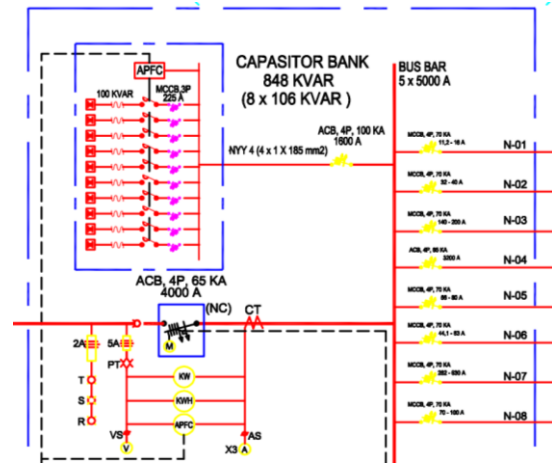


Fig. 3. SLD MDP with capacitor banks

## II. THEORY

### A. Power Triangle

The power triangle depicts a right-angle triangle, which indicates the relationship between Active Power, Reactive Power and Apparent Power as shown in Fig. 1 [4]. True Power is the power consumed or used on an AC circuit. It can also be referred to Active Power or Real Power. Real Power notation is P and calculated in Watts (W). Reactive Power is the power that fluctuates back and moves or responds to the circuit in any direction. The Reactive Power rating is Q which is measured in a Volt-Ampere Reactive (VAR). The product of root-mean-square value of voltage and current is known as Apparent Power. Apparent power notation is S and is calculated in volt amplifier (VA). The following point illustrates how the following Power Triangles are related each other:

- When the circuit voltage V is compounded by an active component of current, it generates Active Power. This is the power that generates engine torque, heat in the heater, etc. The Wattmeter measures this power.
- As a circuit voltage multiplies the reactive component of the current, it provides Reactive Power. This power decides the power factor and flows in the circuit back and forth.
- Apparent Power is the calculation of circuit current which is multiplied by circuit voltage.
- Refer to the Power Triangle, by taking the ratio of True Power to the Apparent Power, it may be defined the Power Factor [5].

$$\text{Power Factor} = \cos \phi = \frac{\text{Active Power}}{\text{Apparent Power}} \quad (1)$$

In the AC circuit, the multiplication of reading Voltmeter and Amperemeter provides the Apparent Power, not the Actual Power. This is so because in the AC circuit, the total supplied power, i.e., the Apparent Power is not solely utilized by the circuit. The power factor of AC circuits with linear loads lies between 0-1 lagging or 0-1 leading as shown in Fig. 4. Generally, it is considered that

if a system exhibits power factor closer to 1, then such systems are said to be stable. As the power factor is a crucial parameter of AC electrical circuits thus correction is quite necessary if the power factor is quite low. Thus, a leading power factor is corrected by the addition of inductive loads. Whereas the correction in the lagging power factor is done by adding capacitive loads.

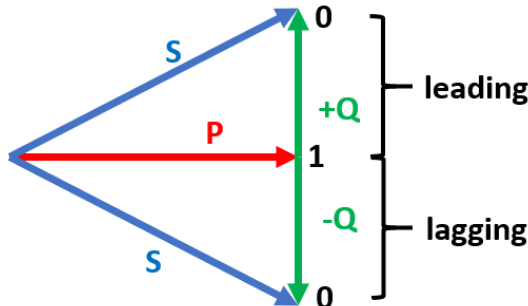


Fig. 4. Power factor diagram

Power factor can be defined as the shifting angle between current wave and voltage wave. Power factor equal to 1 means that there is no shifting angle between current wave and voltage wave. The lagging power factor means that the current wave is shifted negatively than voltage wave, so the current wave is left behind the voltage wave. The leading power factor means that the current wave is shifted positively than voltage wave, so the current wave is led in front the voltage wave. The degree of angle between current wave and voltage wave can be defined as power factor ( $\cos \phi$ )

### B. Capacitor Banks

A capacitor bank is a grouping of several identical capacitors interconnected in parallel or in series with one another. Three phase capacitor banks can be interconnected as delta or wye connection, depend on the needed application. For Low Voltage (LV) distribution lines, capacitor banks as shown in Fig. 5 are interconnected as delta connection to get more reliable compensation for each phase. In order to safety and reliable operations, capacitor banks are assembled in the electrical panel and controlled by the PFR.



Fig. 5. 3-phase LV capacitor bank [7]

Capacitor banks improve the power factor of an AC electrical installation by giving it a proportional of the reactive power consumed by the installation [6]. Capacitor banks can also be used to increase the stored energy in DC power supplies and to boost the power supply's ripple current performance. Electrical or electronic components are single capacitors, which store electricity. Capacitors consist of two conductors that are separated by an insulating material or dielectric. When an electrical current travels through the conductor pair, the dielectric, which reflects the stored energy, generates a static electrical field. This energy stored is not retained forever, unlike batteries because the dielectric requires a certain amount of current leakage, allowing the energy stored to eventually dissipate.

### C. Power Factor Regulator

Power Factor Regulator (PFR) module is the brain of the Capacitor Banks Panel. This module controls connection and disconnection of Capacitor Banks steps in order to maintain the target power factor [7]. It also detects critical operating conditions, such as a power quality disturbance, and protect the power factor correction system. PFR module (Fig. 6) need a sensor which detect a current of a phase and other 2 phases voltage. Current sensor is used a Current Transformer (CT) with secondary current is 5A or 1A. For example, if the CT located to detect R phase, then the voltage detection must be S phase and T phase. PFR module can control several steps of Capacitor Banks and also can be set the capacity of Capacitor Banks at each step.



Fig. 6. PFR module [7]

## III. SIMULATOR DESIGN

The principle of power factor correction is the availability of shifting the angle between current wave and voltage wave. We design a practical simulator which take the advantage of using operational amplifier (op-amp) application [8], such as differential amplifier, inverting amplifier, non-inverting amplifier and all phase filter application. By applying some op-amp applications shown in Fig. 7, we can manipulate current wave using voltage wave. The manipulated voltage wave will compare to initial voltage wave as a power factor.

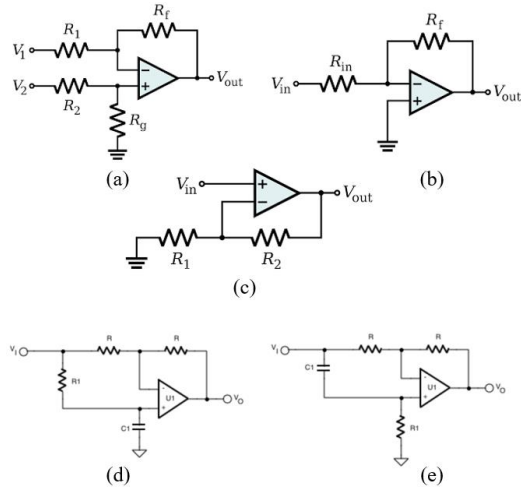


Fig. 7. Op-amp application: (a) Differential, (b) Inverting, (c) Non-inverting, (d) 0° to +180° phase shifter, (e) -180° to 0° phase shifter

The block diagram of the practical simulator is shown in Fig. 8 as below:

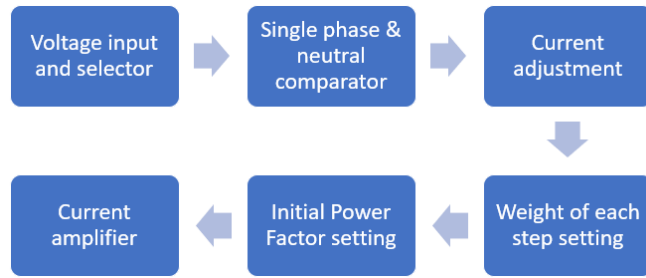


Fig. 8. Block diagram of simulator

#### A. Voltage input and selector

The input of the practical simulator is voltage wave of 3-phase with neutral. Then, the 3-phase voltage will go through the selector switch to select which phase will be processed by the practical simulator. Because we will do manipulation of current wave using voltage wave, we define the voltage selector as current selector of the PFR. Neutral phase directly goes through next stage.

#### B. Single phase & neutral comparator

After selecting the phase, process is continued by calculating the difference amplitude between phase and neutral and decreased the amplitude become 0.1 from the initial. In this stage (Fig. 9), we apply differential op-amp circuit as below:

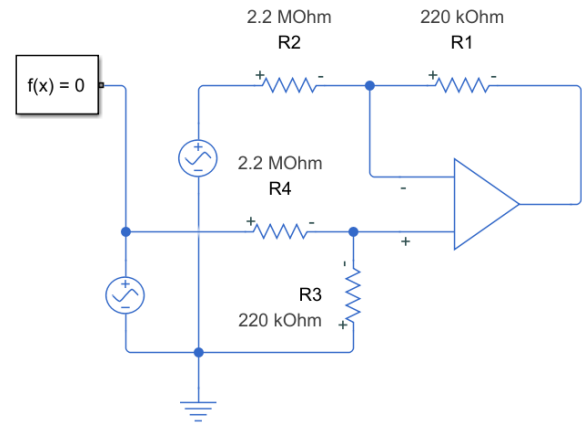


Fig. 9. Differential op-amp circuit

From above circuit, we can define a formula:

$$V_{out1} = V_{Phase} \times \frac{R1}{R2} - V_{Neutral} \times \frac{R3}{R4} \quad (2)$$

#### C. Current adjustment

Next stage, we apply the inverting op-amp circuit to invert the angle for 180° and continue with applying 90° phase shifter op-amp as shown in the Fig. 10. We use variable resistor (VR1) as a reference for current adjustment. The current output will be calculated by a formula:

$$V_{out2} = -V_{out1} \times \frac{VR1}{R1} \quad (3)$$

Shifting angle 90° is got from a formula:

$$Phase (rad) = \tan^{-1} \left[ \frac{\frac{2\omega}{R3.C1}}{\omega^2 - \left(\frac{1}{R3.C1}\right)^2} \right] \quad (4)$$

We define that C1 = 100 nF, then we get R3 = 31831 Ohm.

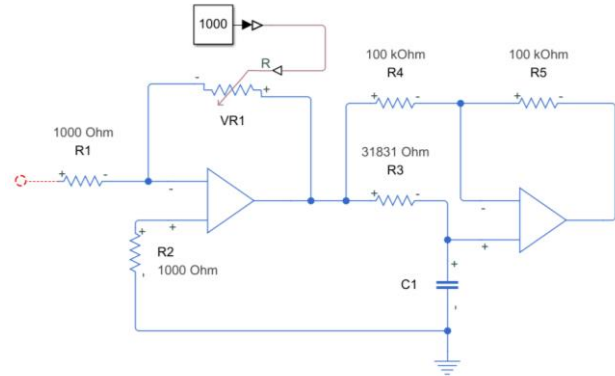


Fig. 10. Current adjustment stage

Fig. 11 the display of oscilloscope showing the shift of the wave. Blue wave is the output wave from previous stage, red wave is the output from inverting op-amp and angle shift to 180°, then orange wave is the output of angle shift to 90°.

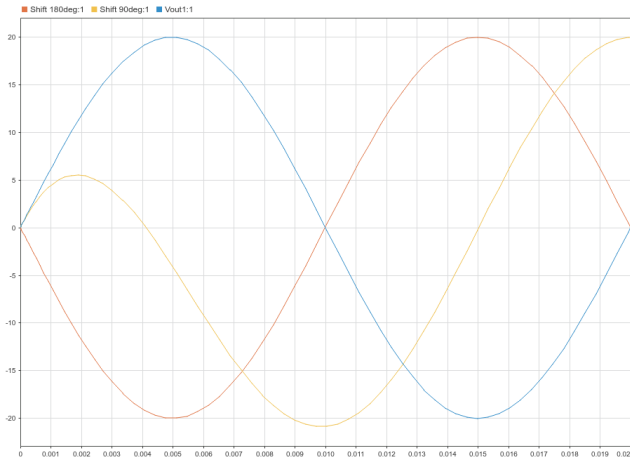


Fig. 11. Angle shift 180° and 90°

#### D. Weight of each step setting

Next process is setting the weight of each step is shown in Fig. 12. We use 12 pcs of variable resistor which represents as 12 steps of Capacitor Banks. This stage is used for shifting the angle and manipulating the power factor become leading. We set the variable resistor so each step can be shifted the angle between 0° and 30°. By using formula (4), with  $C1 = 100 \text{ nF}$ , so the range for each variable resistor will be 0-118795 Ohm.

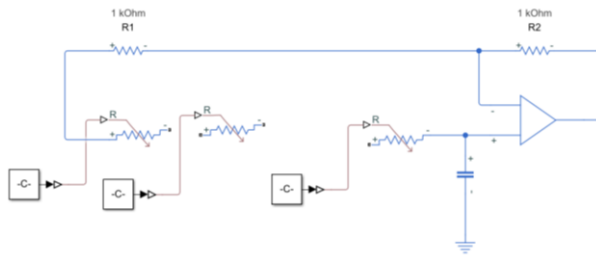


Fig. 12. Weight of each step setting stage

#### E. Initial power factor setting

This stage is the contradiction of previous stage. In this stage, we use the variable resistor to shift the angle and manipulating the power factor become lagging as shown in Fig. 13. We set the variable resistor to make it available shifting the angle from 0° to 90°. Refer to formula (4), the value of variable resistor is 0-31831 Ohm.

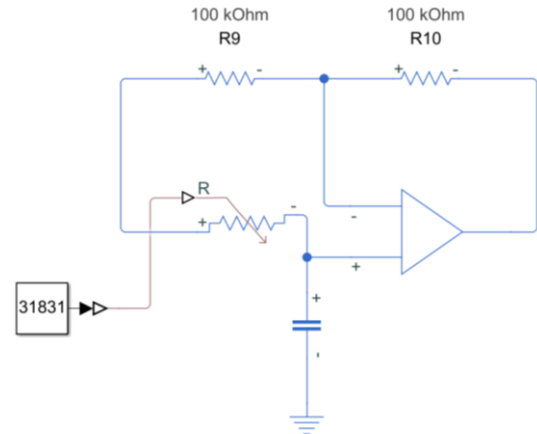


Fig. 13. Initial power factor setting

#### F. Current amplifier

As the final stage (Fig. 14) is current amplifier. This stage is applying non-inverting op-amp application and current-power-transformer to strengthen the current. As specified by the PFR module, the input current sensor is 0-5A, so this stage has a propose to increase the current output of the practical simulator to as the current input to PFR module.

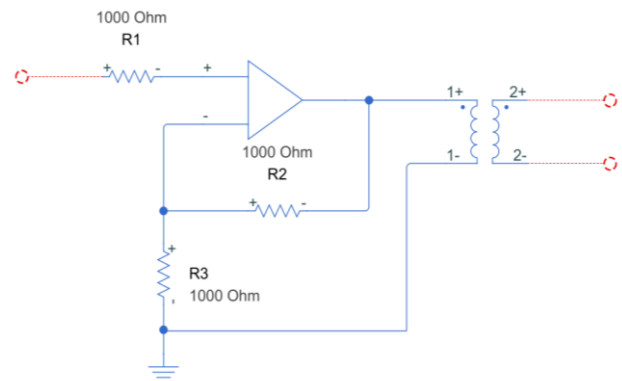


Fig. 14. Current amplifier stage

### IV. RESULT & CONCLUSION

The prototype of the practical simulator for testing Capacitor Banks Panel has already finished. For testing the function of the prototype, we create 3 different experiments with different current sense and voltage sense as below:

- Current sense = R phase, Voltage sense = S - T phase
- Current sense = S phase, Voltage sense = T - R phase
- Current sense = T phase, Voltage sense = R - S phase



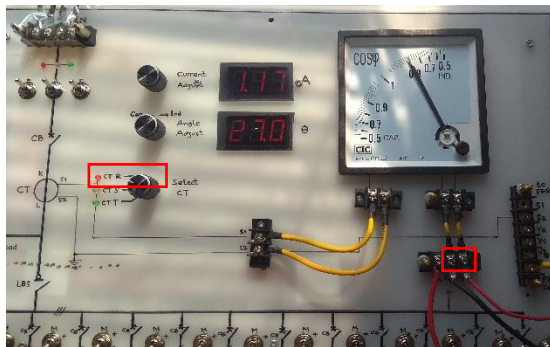


Fig. 15. Testing with current sense = R phase, voltage sense = S-T sense



Fig. 16. Testing with current sense = S phase, voltage sense = T-R sense



Fig. 17. Testing with current sense = T phase, voltage sense = R-S sense

As the result of the testing, the prototype is running well and can be used for testing the Capacitor Banks Panel and its PFR module. It is able to be used to simulate the operation of PFR module for controlling 12 steps of Capacitor Bank with different capacity rating by setting the variable resistor on its step.

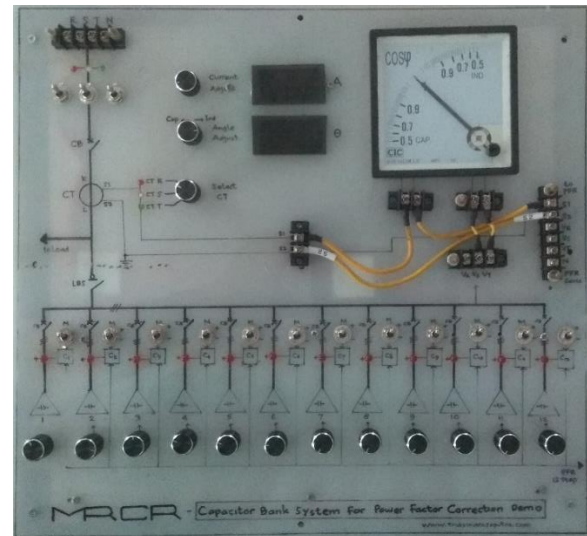


Fig. 18. Prototype of practical simulator

As a conclusion, this practical simulator will be very helpful for panel maker to test the Capacitor Banks Panels and its module. It prevents the failed operation when doing real testing at site with the Load Banks. Besides that, by having a practical simulator, panel maker will save more money.

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