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Smart APFC Employing Fuzzy Logic Controller

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Abstract: The power consumption in industrial settings should be minimized not to incur heavy penalties for excessive use. One of the ways to do this is using an Automatic Power Factor Correction (APFC) unit containing a fuzzy control system. Low power factor and increased power consumption are problems for industrial companies, as utility providers often levy penalties on them. Such penalties are generally assessed to reward consumers into developing a stable and economical pattern of electricity consumption. An APFC unit can be implanted to effectively raise the power factor and thereby reduce total power consumption. It is an electronic device which automatically can adjust the reactive power within an electrical system to a predetermined level of power factor. It also monitors the real-time power factor and make necessary modifications to maintain a system at its optimum operating level. Fuzzy control is a design method for systems based on principles of fuzzy logic. Working with imprecise or uncertain input data and shaking off numbness in a dynamic environment are possible.

The APFC unit can meter out reactive power through fuzzy control techniques in response to changing loads, voltage variations and all the other general operating conditions. The addition of fuzzy control to the APFC unit allows that device to adaptively compensate for real-time conditions. This leads to more effective management of power factor and helps avoid penalties for poor power usage profiles. A combination of an APFC unit and fuzzy control has great advantages for reducing penalties on industrial power consumption. The APFC unit keeps the power factor within acceptable limits, thus reducing penalties paid on account of poor power factor. With the use of fuzzy control, the APFC can compensate for reactive power in response to real-time conditions and energy is used more efficiently this way. With the usage of SD card module, the data can be effectively stored and can further use the data for future technological advancements.

Keywords: APFC, Fuzzy Logic Controller, Power Factor Correction, Industrial Penalties, PZEM 004-T

I. INTRODUCTION

In recent years, there has been a growing concern about the rising energy consumption in industrial sectors. Excessive power consumption not only leads to increased operational costs but also contributes to other issues. To address these challenges, industries are actively seeking ways to minimize their power consumption and improve energy efficiency. One approach that has gained significant attention is the use of Automatic Power Factor Correction (APFC) panels combined with fuzzy logic control systems. Our project aims to introduce the concept of minimizing penalty in industrial power consumption through the implementation of fuzzy logic in APFC panels and highlight its potential benefits for industrial sectors.

Achieving accurate power factor correction is not easy because of dealing with parameters having uncertainties, for example, changes in load, voltage variation etc. Different sources might be responsible for these variations, ranging from the usage equipment shifts to demand changes or loads addition and removal from the system. It is difficult to predict power requirements in real terms given this variation making it hard to maintain the required power factor. Traditional automatic power factor correction systems face challenges in adapting to dynamic load variations due to their fixed or limited control mechanisms. Failure to adjust this may potentially lead to utilities imposing penalties based on inefficient power usage as well as bad power factor corrections affecting its ability to operate properly. Power factor correction systems complexly interact with various electrical quantities like voltage, current, power factor and harmonic distortion. The unpredictability of these interactions leads to difficulties when developing a reliable control algorithm. Furthermore, the dynamics of the power distribution network and its interconnected loads further complicate control strategy development. Besides, an efficient power factor correction requires sophisticated algorithms capable of adapting to any circumstance and continually optimizing power factor.

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The power factor of a system or device is not an exception as it originates from a lot of aspects; each of which has its own contribution to the system or device performance. External influences consist of a wide spectrum from the technological features of operation to the environmental factors which aid the operation of the system. Insight into these elements helps with improving power factor and is crucial for the proper functioning of power systems.

When a system operates near saturation capacity, its power factor gets decreased. However, if the load falls below the rating, then the resultant power factor could be higher. Different mechanisms in conversion processes have efficiencies between low and high contributing to the power factor. For example, dwell motors are anticipated to be more effective than internal combustion engines which are among the most widespread type of engines. Therefore, various sources of energy like solar panels together with others giving higher yield compared to traditional coal-fired plants can influence the system's power factor.The power factor level of a system is greatly influenced by the quality of its component parts. Better system performance may be achieved by raising the power factor with high-efficiency motors and low resistance connections. kVAR is produced by instantaneous loads responding to them, and this improves the performance of the distribution system.

II. PROPOSED METHODOLOGY

The focus of our project is to develop a fuzzy logic based smart APFC unit which can adapt to variations and to exhibit robust performance thereby ensuring stability. With the addition of SD card module, we can store data for performance analysis and further optimization. The project can be implemented in 3 stages: power factor calculation, power factor correction and switching of capacitors.

A. Power Factor Calculation

The power factor refers to the efficiency of power usage. The power factor in an electrical system determines the design quality and effective use of the supply in the electrical system. It is a dimensionless quantity that ranges from 0 to 1. It shows the relation of the real power to the apparent power and is simply the ratio of active power in watts to apparent power in volt-amperes.

$$\cos(\varphi) = P/S$$

where P is the real power and S is the apparent power in the system.

Real power: Real power is the energy that a device uses and transforms into useful functions like lighting, heating, or movement. It's measured in watts and signifies the electrical energy that is efficiently converted into utility. Real power is the part of power that accomplishes tasks in the system, like operating gadgets, engines, or lamps.

Reactive power: Reactive power, in contrast, is the power that moves back and forth between the source and the load in an alternating current (AC) system because of reactive components such as inductors and capacitors. While reactive power doesn't do any work, it is essential for certain types of loads and for stabilizing voltage levels in the system. This power is quantified in volt-amperes reactive (VAR) or kilovolt-amperes reactive (kVAR).

Apparent power: In an AC circuit, apparent power is the combination of both real power and reactive power. This total power includes the power used to perform work and the power that oscillates. Apparent power is typically measured in volt-amperes (VA) or kilovolt-amperes (kVA).

B. Power Factor Correction

The phase difference between the voltage and current waveforms influences power factor in an AC circuit. When voltage and current are perfectly in-phase then power factor equals 1 (100%). This condition represents a unity power factor, which signifies maximum utilisation of available real power. However vitally important is that the phase difference between the voltage and current waveforms affects power factor in an AC circuit. Nevertheless, in most practical cases, because of inductive or capacitive loads, perfect alignment of the voltage and current waveforms causing power factor that is less than unity is missing.

Lagging power factor is a phenomenon in AC electrical systems, which occurs in circuits with inductive loads such as motors, transformers etc. Power factor lag can lead to increased voltage drop in the power distribution system and reduced efficiency due to increased energy losses. A leading power factor in an electrical system is associated with capacitive loads. Leading power factors can boost voltage in power distribution systems due to the capacitive nature of the load. They can also be introduced purposefully to counteract power factor lag and compensate for inductive loads, improving efficiency and reducing losses.

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C. Switching of Capacitors

In power factor correction systems, capacitors are frequently switched ON and OFF to provide dynamic reactive power compensation in response to varying grid conditions. The power factor correction is accomplished through capacitor banks and automatic control systems. An automatically controlled system continuously measures the power factor of the power system. This can be done using power factor controllers or other monitoring tools. The control system analyses the real-time power factor concerning a predefined setpoint. These capacitors are connected to capacitor banks. These banks contain linear/parallel capacitor connectivity or nonlinear/series-parallel capacitor arrangements. Every capacitor bank is engineered to supply it with a definite quantity of compensating reactive power. Capacitor banks are to be equipped with switches that together with reclosing equipment can be employed to isolate them from the power network at the push of a button. The switches can be mechanical contactors or electronic devices such as solid-state switches such as diode-based controlled thyristors and power transistors. By analysing the actual power factor versus the setpoint, the going control system deciphers whether to link or dissociate capacitor banks. The power factor is less than the desired value (indicating an inductive load and a leading power factor) refers to the switching mechanism to link capacitor banks and thereby gives the back an injection of reactive power into the system.

III. FUZZY LOGIC CONTROLLER

A. Design of Fuzzy Logic Controller

The Fuzzy Inference System is pivotal in making decisions within the Fuzzy Logic Controller. This type of artificial intelligence reasons when there is uncertainty using fuzzy logic relating the input variables to the output variables. These include, a fuzzy set of the input variables and a corresponding set of rules, which maps them onto the output variables which are represented by the linguistic variables.
Elements of the Fuzzy Inference System include:
Rule Base: The rule base is a set of if-then rules that link the input and output variables. These guidelines are mostly translated into linguistic sentences depicting the intended message in a professional and polite manner.
Fuzzification Unit: In this stage, imprecise input values are transformed into fuzzy sets through the aid of membership functions. This means, it allows for the representation of imprecise and vague data, thus, creating a much more precise and detailed study.
Decision-making Unit: The decision-making unit is responsible to carrying out operations (AND, OR, NOT) based on predefined rules.
Defuzzification Unit: Once the fuzzy logic steps are done, defuzzification is applied to return the fuzzy output sets into clear output values. This process is significant since it delivers a cleat and correct representation of the system output.

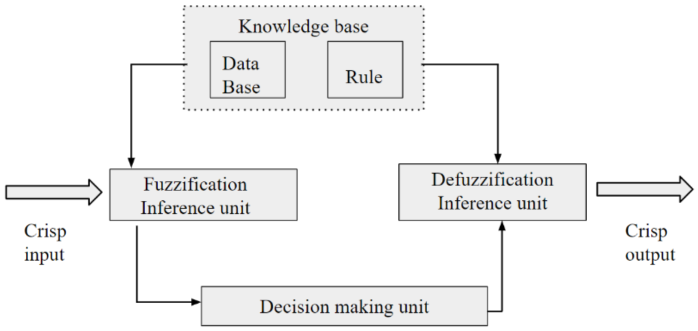

Fig. 1 Design of a Fuzzy Logic Controller

B. Fuzzy Logic Controller in Power factor Correction

The Fuzzy Logic Controller (FLC) which incorporates fuzzy logic in power factor correction provides an adaptive and sturdy setting for handling reactive compensation in electrical systems. In contrast to conventional ways of control with relatively reliable mathematical modelling, the Fuzzy Logic Controller uses linguistic figures and expert knowledge to manage the advanced nonlinear behaviour of power systems and the hardness-like uncertainties in this domain. Fuzzy logic controller relies on fuzzy logic for operation. This logic is for the correlation of imprecise input and output variables as well as human-based problems. Under the power factor correction case, FLC monitors every system's characteristic like voltage, current and power factor and then turns its decision on when and in some measure the need increases.

The FLC uses input variables like voltage deviation, current deviation, and the rate of change of the power factor. These determinants are fuzzified to be mapped in linguistic terms with the help of membership functions for instance "low,"

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"medium," or "high." FLC linguistics out a set of rules that describe the interrelation between the input variables and the output action that is needed. These norms derived from experts' knowledge and experience often ruled these areas. For example, a rule might state: "If the current deviation is very high AND the changing rate of power factor is getting larger, THEN increase reactive power compensation." Based on the fuzzification process of the input variables, using the database rules of fuzzy inference, we can determine the suitable output action. This is implemented by inferring the last layer which involves applying fuzzy operator logic like AND, OR, and NOT on the firing power of each rule to aggregate the values accordingly. The unsharp movement resulting from the logic process must changeover back to a sharp control action. For a centroid-type implement or maxima, an approach is utilized where the desired actual value is saved in a numerical form. Whether through the utilization of capacitor banks or other reactive power compensation devices, the FLC devises the output of the defuzzied one, such that the power factor is harmonized. This control is thus invariably being updated using contemporary observations and feedback from the system.

C. PZEM-004T Sensor Module

The PZEM-004t is a widely used sensor which measures different electrical parameters including volts, amperes, watts, energy, and frequency. It is often employed in power monitoring devices such as Automatic Power Factor Correction (APFC) systems. During the APFC system implementation, PZEM-004t module application is necessary to measure the power supply parameters, like voltage and current at the power supply-load interface. APFC systems aim to improve the power factor by automatically adjusting reactive power to the load, thereby optimizing the efficiency of the electrical system.

IV. IMPLEMENTATION

The simulation of the smart APFC was done and tested in MATLAB Simulink. It consists of a single-phase RL load which is fed by a single-phase AC source. The other main components used include fuzzy logic controllers, capacitors, real and reactive power measurement blocks, scope, and display. The power factor of this electrical system is monitored and the rating of the capacitor (in kVAR) to be added for the correction of power factor is also estimated.

The value of initial power factor is obtained with the help of the following equation.

Initial power factor, $\cos\varphi = \frac{P}{\sqrt{P^2+Q^2}}$

where P is the active power measured and Q is the reactive power measured. The capacitor to be switched for power factor correction is evaluated by the following expression.

Required kVAR = $P(\tan^{-1}\varphi_{1}$ - $\tan^{-1}\varphi_2)$

where 1 and 2 are the phase angles corresponding to the initial power factor and corrected power factor respectively.

The above equation is basically the difference between reactive power associated with the initial power factor and the reactive power associated with the corrected power factor. With reference to the following figure, it represents the difference between AB and AC.

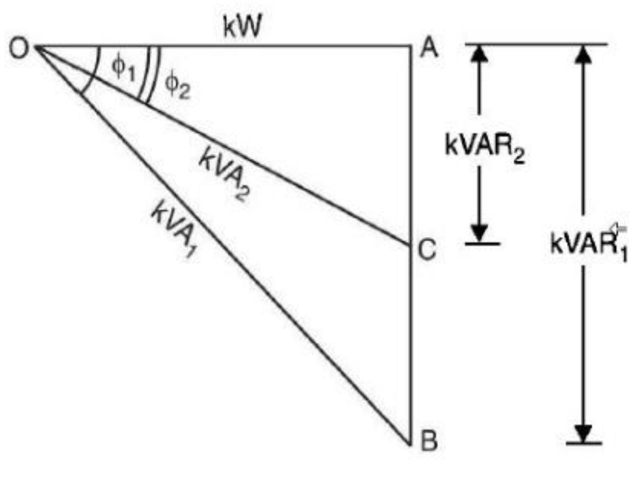

Fig. 2 Calculation of required kVAR

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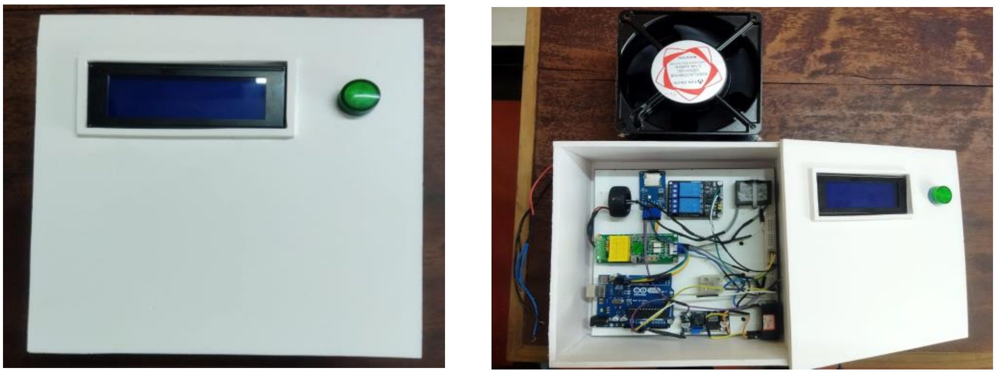
Within the core of the system lies the fuzzy logic controller, a sophisticated algorithmic unit which is designed to make up for the output variations of the input data and perform proper decision making. The initial power factor poses a significant impact on the fuzzy logic controller where it serves well as a controlling parameter. With the help of Fuzzy inference system, which acts as the controller, the decision on which capacitor has to be switched is taken. The possible values of low power factor are of three ranges: 0.80 to 0.85, 0.85 to 0.90 and 0.90 to 0.95. The initial power factor due to industrial loads would lie within one of these ranges, and correspondingly the switching mechanism is activated.

The controller accomplishes this task by means of justifiable and notable calculation to find out the best approach to relay operation. The output of this fuzzy inference system is Boolean values corresponding to the three switching relays, '1' for ON and '2' for OFF. The approach, in essence, means that the capacitor banks can store reactive power whenever necessary and withdraw it whenever a lag in reactive power happens, thus, bringing the power factor as close to unity as possible. The best value that can be aspired for reality is 0.98.

A. Hardware Implementation

The hardware components, which includes an Arduino uno, relay module, PZEM 004-T sensor, LCD I2C 20*4 display, capacitors and loads for the project have been determined by studying related paper and hardware projects. The load selected for our project demonstration is a parallel combination of two 220V AC fans. The LM2596 buck converter is used as a voltage regulator that can step down the input voltage to a lower, regulated output voltage. The Arduino code for the required hardware model includes the fuzzy logic control to switch the capacitor bank depending on the kVAR requirement with the help of relay. As soon as the system encounters a load with lower power factor, the Arduino switches the capacitor of required value to the circuit so that the lagging nature of power factor provided by the load is cancelled by the leading current provided by the capacitor. The switching of capacitor is shown by the AC panel light connected to the system. After each correction process, data including value of power factor, state of capacitor etc gets stored to the SD card with the help of SD card module connected to the circuit. The whole circuit is implemented and framed inside a box with very thorough and careful attention, which enables better proper placing all components.



3(a). Fabricated Case with LCD Display 3(b). Internal Circuit Connected to Fan Load
Fig. 3 Hardware Setup

The circuit built onto a dedicated board; finally protecting the circuit with a housing that contributed to the durability and practicality during its deployment. The output parameters of the PZEM 004-T are then stored using a SD card module, attached to the Arduino. With the implementation of the data logging, data can be stored for researchers to use for past analysis and reference in the future. This module acted not only as a purely electronic medium, cheap storage solution but also allowed thorough post-analysis and archival purposes. Any extension and compliment brought more robustness, functionally and usability to the project.

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V. RESULTS AND INFERENCE

The electrical parameters measured after connecting the load is shown in the LCD display. When the load is connected, PZEM 004t will sense the electrical parameters and this data gets stored in the SD card module. Since the load connected is of inductive nature, power factor decreases. The power factor after connecting the load is displayed as **0.87**.

As soon as the system detects a lower power factor than the reference value, the fuzzy logic controller, with help of relay module, switch the capacitors and make the power factor a higher value. After power factor correction, the power factor increases to **0.99**, which is indicated by the panel light.

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