Development of a Fuzzy Logic Power Optimization System for a Refrigeration Plant

Tawanda Mushiri, and Charles Mbohwa

Abstract**—**Despite the fact that electrical power is a major overhead in industrial refrigeration plants, this resource still lacks full utilization in some plants of some organizations in developing countries. An unfortunate consequence of this predicament is that these organizations end up paying for more power than they have actually consumed or even necessarily need. This research however addresses solutions to the above concerns through the development of a power optimization system. Since power optimization is a broad subject the scope was only limited to power factor correction and compressor capacity control. The developed optimal design consisted of replacing part of the inductive load by a fuzzy controlled synchronous motor. The torque angle at the synchronous motor shaft was continuously regulated by the automatic compressor capacity control schematic. Simulations carried out using MATLAB RB2010 are also presented.

Keywords**—**Power factor, compressor capacity control, fuzzy logic and synchronous motor.

I. INTRODUCTION

PLANT optimization of energy consumption has been regarded as an important goal for many industries (Shaefer, 1997).In its most general meaning, optimization is the effort and process of making a decision, a design, or a system as perfect, effective, or functional as possible. Optimization has been defined as the process of finding the conditions that give the maximum or minimum value of a function of certain decision variables subject to restrictions or constraints that are imposed. Optimization may be the process of maximizing a desired quantity or minimizing an undesired one .In refrigeration plants where electrical power costs are a major overhead cost the above issue is of great concern. Especially during these hard economic times where organizations are in a greater need to reduce production overheads so as to sustain marginal profits. This case study based research however presents a power optimization system for a refrigeration plant. Since power optimization is a broad subject this research will focus only on power factor correction and compressor capacity control.

A. Power Factor Correction

In general however power factor is a measure of how effectively electrical power is being used. The higher the power factor, the more effectively electrical power is being used and also the contrast is true (Rashid, 2001). By definition in single phase ac systems power factor is the ratio of the true power flowing to the load to the apparent power in the circuit.

$$\left[p.f = {}^{true\ power}/_{apparent\ power}\right]$$

In general an industrial plant typically poses inductive loads such as transformers, induction motors, induction furnaces, welding plant and fluorescent lighting. The presence of inductive loads is the major cause of low power factor in the electrical system of consumer plants. The negative repercussion incurred by a consumer plant which has low power factor include: high monthly energy bills, power factor penalties, decreased load handling capacity, increased line losses and also potential risk of equipment failure due to excessive currents flowing within the distribution system ((Meier, 2006). Various power factor correctional measures are already on existence on the market and these ranges from the use of capacitor banks, active power filters, synchronous condensers, synchronous motors, etc. (Kepka, 2010). Factors of consideration when choosing any of these correctional measures include: cost, required efficiency, maintainability, reliability, availability and also power utility regulations.

B. Compressor Capacity Control

For compressor operators, maximizing efficiency and minimizing energy costs are key elements. Because of industry standards and other unknown variables, compressors are typically built oversized to run over capacity. Process reciprocating compressors work much in the same way as the cruise control mechanism in a car. As the car goes uphill and the cruise control is set at a specific speed, the car increases its throttle to maintain the specified speed; going downhill, it decreases its throttle. Because reciprocating compressors are not variable capacity machines, “cruise control” – variable capacity control – is necessary to minimize wasted energy and thus reduce energy costs. Exerting this throttle over the compressor allows you to save operating energy and reduce energy costs (Stoeker, 1998). The positive displacement nature of process reciprocating compressors is such that you

Tawanda Mushiri, D.Eng. Student, University of Johannesburg, South Africa. Email Id: tawanda.mushiri@gmail.com

Charles Mbohwa, Professor and Supervisor, University of Johannesburg, South Africa. Email Id: cmbohwa@uj.ac.za

basically run it at full capacity or you turn it off. As such, they often require devices to regulate (reduce) capacity and help operators maintain process control. This is typically done with a combination of stepped unloading systems and a gas recycle loop, usually referred to as a bypass. The interested reader is referred to explore (Grasso Refrigeration division, 2010).

II. BACKGROUND

The dual stage refrigeration plant of the organization under study had low power factor (monthly average 0.72) which was below the mandated utility value of 0.95. The predicament had also been further worsened by the fact that the compressors at the organization had an inefficient compressor capacity control scheme. The compressor operation was maintained at 100% duty cycle full load capacity regardless of the fluctuation in refrigerant demand. The main drivers or actuators of these compressors were several induction motors. These induction motors were considered to be a major electrical power consumer load in the plant of the company. The monthly average energy demand of the plant was 640KVA. The problems of concern at this particular organization included high electrical energy bills, power factor penalties, decreased load handling capacity. The organization required an efficient (but minimal cost) power optimization system using the already available materials in the plant.

A. Aim

To develop an affordable, stable and efficient power optimization system for the refrigeration plant..

B. Objectives

i. To maximize electrical power utilization in the plant through improvement of the power factor from 0.72 to 0.98 through dynamic reactive power compensation.

ii. To minimize plant power losses through the development of an efficient automatic compressor capacity control scheme

iii. To employ fuzzy logic in overall controller synthesis for the two processes.

III. METHODOLOGY

A case study approach was adopted in this research. The main reason for employing this type of research was to ascertain the necessary process definitions which would give an approximation of the exact process parameters needed for design development specifications. Mainly the data was acquired through site visits, document review, literature review and interviews. Experiments through modeling and simulation were carried out using MATLAB RB2010 so as validate the development success.

IV. DESIGN DEVELOPMENT

In general optimal system design is mainly governed by the design cost and required efficiency of the particular system. Other factors which are also taken into consideration are safety, operability, reliability, availability and maintainability of the system.

A. Power Factor Compensation Development

In order to reduce the design cost the already available material was utilized in the modification of the plant so as to adequately compensate for reactive power. Generally speaking in most refrigeration plants the major inductive load is contributed by induction motors which are used to actuate the major compressors. Hence an optimal power factor compensation design would be to replace part of the inductive load with the use of synchronous motors. Synchronous motors operated in the overexcited mode deliver reactive power instead of absorbing it. In this manner they act as synchronous capacitors and are useful in improving power factor. In a factory having many induction motors (a lagging power-factor load), it is often desirable to have a few machines act as synchronous capacitors to improve the overall power factor (Beaty, 2001). A synchronous motor is also a mechanical marvel which can be used for dual purpose such as reactive power compensation and also actuating a mechanical load such as a compressor.

However in industry the most widely adopted power factor correction method is the use of capacitor banks. Though this method has its merits it still faces limitations such as:

i. it does not provide dynamic reactive power compensation

ii. may causes spikes during capacitor switching and

iii. Likely to increase signal distortion in the presence of current harmonics.

Another important factor worth taking into consideration is the issue of cost; as such a factor will deter the implementation of a project. To the consumer plant capacitor banks offer only reactive power compensation unlike the synchronous motor which can offer both reactive power compensation and actuating a load. This might be useful especially in refrigeration plants. Nevertheless the synchronous motor is not without its limitations. Basing on the above factors the proposed design consisted of replacing part of the induction load by a synchronous motor. The replaced inductive load consisted of an induction motor which was specifically being used for actuating a compressor.

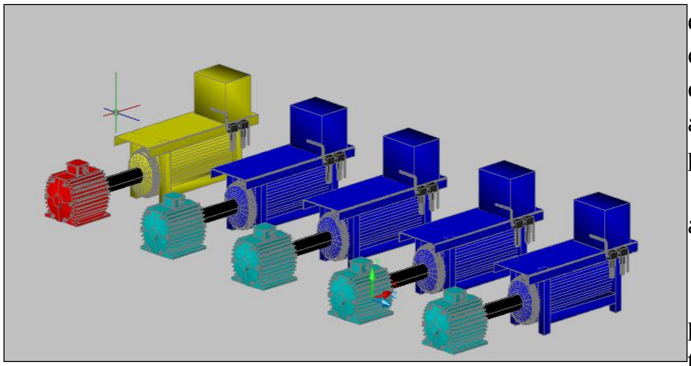

Fig. 1 Solid model of five compressors

The Fig 1 shows a solid model drawing which is an illustration of five industrial compressors in the refrigeration plant of the organization under study. The compressors are actuated by induction motors. If part of the inductive load is replaced by a synchronous motor power factor can be compensated. The synchronous motor (depicted red in fig 1) is driving a mechanical load and also providing reactive power compensation to four other induction motors (depicted light blue in the fig 1). Careful sizing and control is needed such that the synchronous motor has the capability of providing the actual required reactive power and also the ability to drive a mechanical load. Also excess reactive power can be detrimental to the electrical distribution system. The output torque at the synchronous motor shaft can be regulated by automatic compressor capacity control

a) Determination Of The Amount Of Reactive Power Required For Power Factor Compensation

In order to improve the overall electrical system power factor from 0.72 to 0.97 we need to determine the amount of reactive Q power which needs to be added or compensated to the electrical system. It is necessary at this point to highlight that we also need to know the level of harmonic contamination in the plant. If the harmonic contamination level is minimal we employ the use of displacement power factor equation:

$$\left[p.f = {}^{vi\cos\emptyset}/_{vi} = \cos\emptyset\right]$$

Where: v is the root mean square voltage, i is the root mean square current and $\emptyset$ is the phase difference between the current and voltage waveform.

In single phase circuits power factor can be regarded to be the absolute value of the cosine of the phase difference between the voltage and current waveforms. However if in another case the harmonic contamination in an electrical system is above the minimum levels the power factor can be considered to be:

$$\left[p.f = \cos\emptyset * \frac{1}{\sqrt{1} + THD^2}\right]$$

Where: cosϕ is called displacement power factor and $\frac{1}{\sqrt{1}+THD^2}$ is called distortion power factor.

The power factor which is calculated as the product of the displacement power factor and distortion power factor is called total power factor p.f. Total power factor correction can only be achieved when both displacement power factor and distortion power factor are corrected requires a two-step process:

1. Reduction of the displacement angle between voltage and current.
2. Reduction of the total harmonic current distortion.

If either of these steps is taken without the other the total power factor will be increased but it may not be high enough to reach the minimum value required by the utility (Sandoval, 2012) Additionally, if one step is taken without the other, the Total Power Factor Correction and the corresponding efficiencies will not be achieved. According to the power triangle.

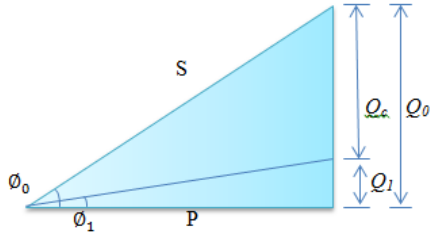

Fig. 2 Power Triangle

Fig 2 has also been extracted from (Sandoval, 2012). Where: S represents the apparent power, Q0 represents the reactive power, P represents the true power and $\emptyset_0$ is the initial displacement power factor angle and $\emptyset_1$ is the new displacement power factor angle. From the power triangle it can be seen that by varying the reactive power Q0 in the system the displacement power factor angle $\emptyset_0$ can be adjusted. Thus by adding a specific amount of reactive power Qc to a lagging power factor system we can bring it to the desirable standards ie $0.95 \leq \cos\emptyset_1 \leq 1$. For the case under study it was required to compensate a lagging power factor of 0.72 to 0.98. Hence the amount of reactive power Qc to be supplied by an external capacitive source is:

First from the power triangle we can deduct $\left[{}^{P}/_{S} = \cos\emptyset_0\right]$ and $\left[{}^{Q}/_{P} = \tan\emptyset_0\right]$

- ➢ Required Reactive Power Qc = Initial Reactive Power Q0 – Reactive Power of new p.f Q1
- ➢ Qc = Ssin$\emptyset_0$ – Ptan$\emptyset_1$

  For the case under study
- ➢ Qc = 640kVAsin(cos-1(0.72)) – 460.8tan (cos-1(0.98)) = 350.57kVar

b) Synchronous Motor Sizing

The synchronous motor in this case study is being used for dual purpose that is for power factor correction and driving a mechanical load. Hence when the overall system power factor is 0.72 lagging the motor should have the power capability of providing a reactive power Q of 350.57kVar and a mechanical load P of 55kW

c) Operational Power Factor Of The Synchronous Motor

In general if a synchronous motor is operated at successively smaller torque angle and also higher excitation the motor has the ability to produce reactive power kVars. It now acts as a capacitive source. This reactive power can be given by:

$$\left[Q = \sqrt{[V_t]^2\,[I_a]^2 - P^2}\right]$$

Where: Q is the reactive power; P is the working power/true power and $[V_t]^2\,[I_a]^2$ *represents the apparent power.*

As highlighted before over excitation results in the synchronous motor operating at leading power factor thus supplying reactive power to the system. Hence for the case under study the synchronous motor has to supply reactive power of the magnitude of 350.57kVar and 55kW mechanical power therefore it should be operated at a leading power factor of:

$\emptyset = tan^{-1}[Q_c/P]$, using the power triangle

$\emptyset = tan^{-1}[350.57/55] = 81.08$

Hence $\cos\emptyset$ = 0.15 leading

This implies that the synchronous motor should be operated at a power factor of 0.15 leading to compensate for a lagging electrical system power that of 0.72. The following graph shows the different power factors at which the synchronous motor is operated so as to compensate the different lagging electrical system power factors in order to maintain the overall electrical system power factor at 0.98. For example at a lagging electrical power factor of 0.8 the synchronous motor should be operated at 0.193. The graph can be considered to be non-linear especially since the graph only represents the electrical system power factor in the lagging state only. Considering the fact that we a using a synchronous motor for compensation it means that the electrical system power factor can also become leading.

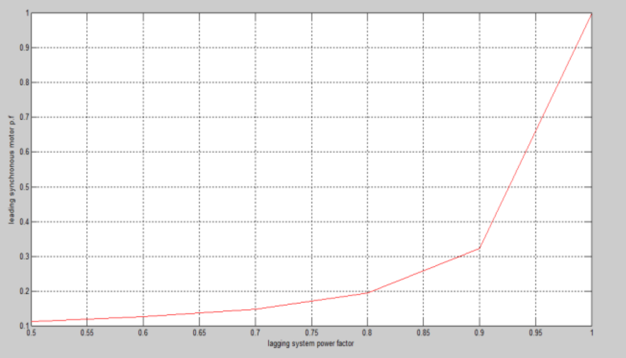

Fig. 3 Relationship between overall system power-factor versus synchronous motor power factor.

Having determined the required size for the synchronous motor we now model it on line with the other motors on the electrical distribution of the organization understudy. The simulation was carried out so as to determine the power flow and the power factor value determined

d) Power Flow And Power Factor Simulation For The Case Under Study (Matlab 2012 Software)

Fig 1.4 shows a simulation model of four induction motors placed on line with the sized synchronous motor. The specifications of these electrical machines which were used for this model development have been obtained from the parameters of the case study organization. The electrical power supply of the case under study is from a11kV transmission line to the plant main transformer 3.5MVA /480V. In the plant the five compressors are actuated by induction motors of different horse powers which range from 260kW to 55kW. At constant load conditions the **POWER SYSTEMS SIMULINK** model proved that power factor could be maintained at 0.98 when the synchronous motor is place in line with the other induction motors. However the load conditions in a refrigeration plant are dynamic hence an efficient controller is needed so as to maintain the power factor in the desired ranges.

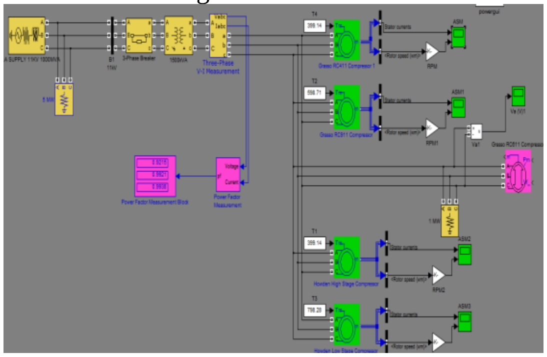

Fig. 4 Power system Simulink by MATLAB RB2010

B. Controller Development

The task of modelling complex real-world processes for control-system design is difficult. Even if a relatively accurate model of dynamic system can be developed, it is often too complex to use in controller development as much simpler (e.g. linear) process model is required by most of the conventional control-design techniques (Carr and Shearer, 2007). For many practical problems, it is difficult to obtain an accurate yet simple mathematical model, but there are human experts who can provide heuristics and rule-of-thumb that are very useful for controlling processes (Rashid, 2001). Also much of the decision making in the real world takes place in an environment in which the goals, the constraints and the consequences of possible actions are not known are precisely (Rashid, 2001). The above notions cement the use fuzzy logic as a control methodology which is used to deal with complexity, vagueness and imprecision of practical system. Fuzzy logic controllers have been known to usually outperform other controllers in complex, nonlinear, or undefined systems for which a good practical knowledge exists (Carr and Shearer, 2007). Human operators have been known to be capable of controlling the process effectively yet they do not know the underlying control dynamics.

The above factors brought about the motivation of using fuzzy logic in the controller development for the control of the synchronous motor.

a) Fuzzy Controller Model Development

The design process of the fuzzy logic controller (FLC) has five steps: selection of the fuzzy control variables, •membership function definition, rule creation, inference engine, and defuzzification strategies (Rashid, 2001). In this research the general principle used is that in order to compensate for a lagging electrical system power factor the synchronous motor has to provide sufficient reactive power Qc to the electrical system. Simply speaking the synchronous motor would have to be operated at a certain level of over excitation (or leading power factor). Hence the choice fuzzy control variables for controlling the synchronous motor were

b) Input control variables

i. Overall electrical system power factor level [sys p.f_state]
ii. Synchronous motor terminal power factor value [synch p.f_state]

c) Output control variable

i. Output reactive power change [synch p.f_change]

Each of the two fuzzy input control variables was assigned triangular membership function with seven membership sets. The seven sets in the triangular membership represent a power factor change from High Lagging (HLg), Medium Lagging (MLg), Low Lagging (LLg), Unity (U), Low Leading (LLd), Medium Leading (MLd) and High Leading (HLd).

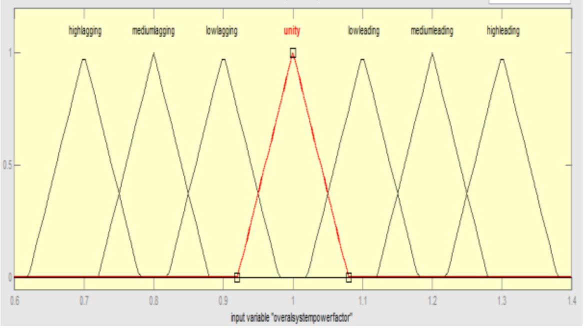

Fig. 5 Input variables on MATLAB fuzzy logic model

Both of the input control variables were assigned the above membership function. For each of these fuzzy control variables the degree of membership has been normalized to [0:1]. *Please note that in the fig above the power factors values which are shown greater than 1 are leading. For example 1.1 represents a power factor of 0.1 leading and likewise 1.2 represents a power factor of 0.2 leading. Power factor is a ratio which should be between 0 and 1 however the above representation was only used so as to indicate the power factor state ie leading or lagging.*

d) 0utput Control Variable: Output Reactive Power Change

This fuzzy kvar controller compares the existing overall electrical system power factor to the existing synchronous motor power factor. It then absorbs or supply extra reactive power to the system depending on the anomaly in the system. The reference point is the required power factor level that is unity. The output reactive power factor change gives use the dynamic excitation level which is needed to maintain the power factor in desired conditions.

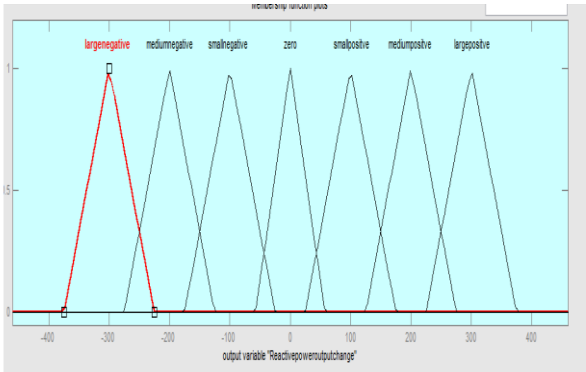

Fig. 6 Output variables on MATLAB fuzzy logic model

Also the output variable has been coded into a triangular membership function with the following sets Large Negative (LN), Medium Negative (MN), Small Negative (SN), Zero (ZE) SP (Small Positive), Large Positive (MP) and Large Positive(LP).Negative represents the absorption of reactive power and Positive represents the addition of reactive power by the synchronous motor

e) Rule Development

The design techniques for fuzzy controllers can be classified into the trial-and-error approach and the theoretical approach (Rashid, 2001) in the trial-and-error approach, a set of fuzzy if-then rules are collected from human experts or documented knowledge base, and the fuzzy controllers are constructed from these fuzzy if-then rules. The fuzzy controllers are tested in the real system and if the performance is not satisfactory, the rules are fine-tuned or redesigned in a number of trial-and-error cycles until the performance is satisfactory. In theoretical approach, the structure and parameters of the fuzzy controller are designed in such a way that certain performance criteria are guaranteed. Both approaches could be used at the same time. The developed fuzzy control rules are summarized below.

TABLE I
CONTROL RULE TABLE

	Overall Electrical System Power Factor Value							
		HLg	**MLg**	**LLg**	**U**	**LLd**	**MLd**	**HLd**
Synchronous Motor Power Factor Value	**HLg$_m$**	MP	SP	ZE	SN	MN	LN	LN
	MLg$_m$	SP	ZE	SP	MP	SP	MP	LP
	Lg$_m$	LP	LP	MN	LN	LN	LN	LN
	U	LP	MP	SP	ZE	SN	MN	LN
	Ld$_m$	LP	LP	LP	SP	ZE	SN	MN
	MLd$_m$	LP	LP	LP	MP	ZE	LN	SN
	HLd$_m$	LP	MP	MP	MN	MN	ZE	ZE

The following is rules were created by **MATLAB 2010 FUZZY TOOL BOX and the Rule** view is also shown below. The Rule Viewer displays a roadmap of the whole fuzzy inference process. It is based on the fuzzy inference diagram described in the previous section.

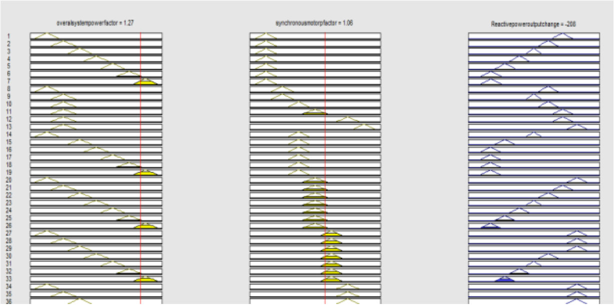

Fig. 7 Fuzzy logic rules

Defuzzification creates a combined action fuzzy set which is the intersection of output sets for each rule, weighted by the degree of membership for antecedent of the rule and produces a non-fuzzy control action that represents the membership (function of an inferred fuzzy control) action.

f) Fuzzy Kvar Controller Results

The following controller performance results were obtained. It can be observed that at exactly unity overall electrical system power factor there is no reactive power addition or absorption. It can also be seen that when the overall electrical system power factor is lagging the controller compensate by additional reactive power. The controller performance can be viewed as satisfactory as it is responding appropriately and adequately to the power factor changes.

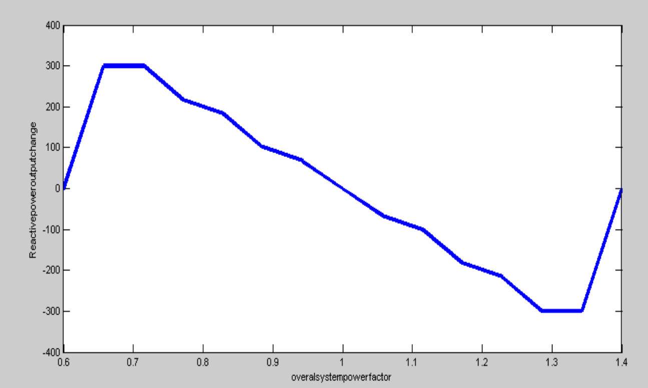

Fig. 8 Overall system power factor

An efficient excitation mechanism should be used with this proposed controller. It is worthwhile to suggest the use of solid state automatic excitation control in the regulation of the dc field of the synchronous motor so as to control the motor's operational power factor. A major merit of fuzzy logic is that it can be blended with these convectional techniques to achieve greater positive results

C. Compressor Capacity Control Development

In general compressor capacity control enables the reduction of operational the compressor actuated by the synchronous motor was supposed to act as a trim compressor. A trim compressor is supposed to be operated at full load capacity(Stoecker, 1998).The benefits of compressor capacity control is that it would ensure that a specific mechanical load is maintained at the shaft of the synchronous motor (hence a specific torque angle). Increasing the mechanical load at the synchronous motor would reduce its ability to produce reactive power. The other benefit of compressor capacity control would be to reduce the running of lightly loaded motors this in turn would increase the overall system power factor at the same reducing power losses. Basing on the plant parameters of the case under study the compressors were of Grasso type mainly reciprocating. The several compressor cylinders were 4, 6, 9 respectively. Hence an appropriate method of compressor capacity control would be to automatically control the sequential cylinder loading and unloading. For the Howden screw compressors an appropriate compressor capacity control scheme would have to be developed. Due to the fact that every refrigeration plant has its own specific operation procedure the developed capacity control scheme should comply with the refrigeration laws. At this point in time the researchers would leave this as an area needing further research**.**

V. CONCLUSION

The development of above fuzzy logic controller was based on trial and error method and by using this method the controller was supposed to guarantee the a certain performance criterion for dynamic power factor correction. Though the results obtained were satisfactory there is still need for fine tuning and stability analysis of the controller in a real system.

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