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Automatic Power Factor Correction for Variable Inductive Load Industries: A Case Study of Resources Improvement and Manufacturing Company Ltd (Rimco)

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Abstract- Power factor Correction Optimization for inductive loads by using an automatic power factor compensator has been achieved in this work. The case study industry was modelled as an RL load and global compensation method of each section of the industry was the technique selected for the compensation so as to eliminate the cost of installing various smaller compensators on each machine. i.e. each section of the industry was lumped up and compensated from a suitable point. The circuit was achieved by connecting 4 capacitors in parallel on each phase for each section (12 capacitors per section). The capacitors were connected through a switching contactor. The AT89c51 microcontroller was programmed such that it automatically checks the capacitance required for a unity power factor and then produces a switching pattern for the contactors such that the capacitance in circuit at all times always achieves unity power factor. A cost analysis was also done in this work using the tariff of EEDC as at Dec 2017 to see the amount being saved as a result of compensation. The result showed the automatic compensation circuit was able to save the industry about 516 KVA in apparent power, reduce the total reactive power of the industry by as much as 1464 KVAR and about 9 million (55%) of their utility bill when the operating power factor was 0.74 and the utility bill was N37.83 per KVAh .

Indexed Terms- power factor, inductive load, capacitor bank

I. INTRODUCTION

This In industries, most of their loads are composed of motors, pumps and machines which have windings. These kind of loads are mostly inductive loads and being inductive, they tend to increase the phase angle which in turn reduces the power factor of operation. An industry operating on a low power factor has some inherent disadvantages some of which include an increase in the metered power consumed by the industry, an increase in the harmonic contents of the electric power supplied, a reduction in the life span of the machines due to the resultant higher current value among others. Owing to these disadvantages, it is imperative for industries to have a method of countering the effects of the inductance thereby improving the power factor. This may be achieved by connecting capacitors of the right size across the inductive loads to cancel out their effects. Getting the right size of capacitors to connect is of utmost important as connecting a wrong size would either make the load more capacitive or will still leave the power factor at a low value which defeats the aim of using the capacitors.

Power factor correction is hence the connection of active, reactive devices which are capacitors or inductors to alter the phase angle between the voltage and current of an industrial or residential supply. This alteration to the phase angle improves the power factor of the supply and hence improves the quality of the power supply. Improving the power factor of an industrial load has some inherent advantages such as a reduction in the metered power measured by the utility companies which lead to a reduction in the monthly bills of the industry, a reduction in the harmonics and current of the supply which leads to a reduction in the wear and tear of the moving parts of the machine due to a reduction in current (by extension the torque) required to run the machine among others.

This work seeks to design and simulate a method to constantly adjust the capacitors in circuit so as to correctly cancel out the effects of the inductive load.

The circuit designed in this work constantly monitors the inductive reactive power of the system and then adjusts the capacitors in steps so that irrespective of the load in circuit, the circuit would adjust the capacitive reactance to the right value such as to cancel out the inductance of the entire industry.

II. FORMULA FOR DETERMINATION OF CAPACITOR TO BE INSTALLED

When compensating capacitors are connected across the industry, the phase angle is altered from φ to φ'. Since the capacitors are considered ideal, they do not consume any power hence the active power of the system remains the same before and after compensation. However, the reactive power and apparent power of the industry is also altered which brings the power triangle to figure 1 below. For $\varphi^1 < \varphi$, we will get: $\cos\varphi' > \cos\varphi$ and $\tan\varphi' < \tan\varphi$.

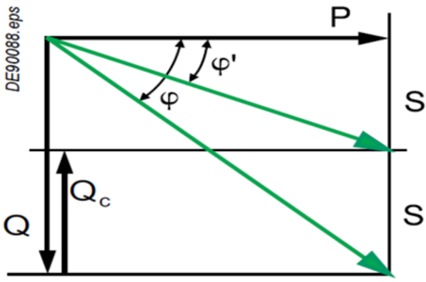

Figure 1: Power Triangle for compensated system

From figure 1, φ' is the new phase angle as a result of adding capacitors with reactive power as Q_c, Q is the reactive power of the entire system, S^1, S is the apparent power of the system. Hence from figure 1, assuming Q_n is the reactive power gotten after adding the capacitance, then

$$Q = Q_c + Q_n$$

Making Qc subject of the formula gives

$$Q_c = Q - Q_n$$

From equation above and the power triangle diagram,

$$Q = P\tan\varphi$$

Substituting we get

$Q_c = P\tan\varphi - P\tan\varphi'$(Since φ' is the phase angle after adding capacitance)

Hence, $Q_c = P(\tan\varphi - \tan\varphi')$

Where

Qc is the capacitive reactance of the compensation capacitors to be installed in VAR,

φ is the phase angle of the system before compensation capacitors are installed and φ' is the phase angle after the capacitors are installed or the phase angle desired after compensation.

Conversion of industrial load to RL load

Since the industry load is mostly inductive, we can assume the entire load of the industry to be basically a series RL circuit with the apparent power and active power as gotten in table 2. Hence, the total equivalent inductance and resistance of the industry load can be gotten from the reactive and active power.

$$S = \sqrt{3}IV$$

But from ohms law, V = IZ where Z is the impedance in ohms

Hence for three phase system, $P = 3I^2Z_{\mathrm{phase}}\cos\varphi$

a) Solvent Plant Section

$I = 738.65$, $\varphi = \cos^{-1}0.74 = 42.2686$ and $P = 402.55e^3$

Then $402.55e^3 = 3 \times 738.65^2 \times Z_{phase} \times 0.74$

$$Z_{phase} = \frac{402.55e^3}{1211.240e^3} = 0.3323\Omega$$

From impedance triangle,

$$R = Z\cos\varphi \;\; and \;\; X_L = Z\sin\varphi$$

Then $R = 0.3323 \times 0.74 = 0.2459\Omega$

And $X_L = 0.3323 \times \sin 42.2686 = 0.2235\Omega$

Now $X_L = 2\pi f l$

Hence $l = \frac{0.2235}{2\times3.142\times50} = 7.1145e^{-4}\ H$

$l = 0.71145\ mH$ And R = 0.2459Ω

Hence the RL circuits for each section as calculated above can be seen as compiled in table 1 below

Table 1: calculated RL load for the various sections

S/N	SECTION	R(Ω)	L(MH)
1	Solvent plant	0.2459	0.71145
2	New boiler	0.5225	1.51155
3	Old boiler	0.5436	1.57256
4	Refinery plant	0.9305	2.69171
5	PK mill expeller	0.118	0.3418
6	PK mill central panel	0.8267	2.39137
7	Workshop machines	1.2420	3.95301
		3407.59	1806.59
	Total		

III. DESIGN AND SIMULATION PLATFORM

A basic aspect of the Simulink platform is Sims cape. Sims cape provides an environment for modelling and simulating physical systems spanning mechanical, electrical, hydraulic, and other physical domains. It provides fundamental building blocks from these domains that you can assemble into models of physical components, such as electric motors, inverting op-amps, hydraulic valves, and ratchet mechanisms. Because Sims cape components use physical connections, the models match the structure of the system being developed. (Mathworks, 2013)

a) Mathematical Implementation

The formulas and equations derived in the previous section are applied here to get the component values for the design and the parameters (voltage, current and power) at every stage of the design process so as to be able to ensure the components used are not below the voltage and current ratings at its point of usage.

Table 2: The load properties of the case study

S/N	SECTION	I (A)	P (KW)	S(KVA)
1	Solvent plant	738.65	402.55	530.9
2	New boiler	339.1	180.24	243.7
3	Old boiler	322	169.1	231.5
4	Refinery plant	172.54	83.1	124.0
5	PK mill expeller	1513.1	810	1087.6
6	PK mill central panel	187.3	87	134.6
7	Workshop machines	134.9	74.6	97.0
		3407.59	1806.59	2449.3
	Total			

The power factor of the entire industry is given by

$$\frac{Total\ Active\ power\ (Kw)}{Total\ Apparent\ Power\ (KVA)} = \frac{1806.59}{2449.3} = 0.74$$

This is the operating power factor of the factory. However, in Nigeria, the supply power factor is generally poor and unsteady hence the power factor of the industry.

Table 3: Specifications table

S/NO	PARAMETERS	SPECIFICATIONS
1	system Voltage, V_{in}	415 VAC
2	System frequency, f_s	50 Hz
3	Apparent Load Power	2449.3 KVA
4	Power factor	0.74

Table 4: capacitances for each section as calculated to bring the power factor of each section from the lowest value (0.7) to the highest (0.96)

b) Determination of Capacitor Steps

S/NO	SECTION	CAPACITANCE (MF)
1	Solvent plant	39.39
2	New Boiler	17.63
3	Old boiler	16.54
4	Refinery plant	8.127
5	PK mill expeller	79.23
6	PK mill central panel	8.51
7	Workshop machine	7.269

For this work, the capacitors were made to be connected in 4 steps with the capacitors having varying capacitances. The capacitance values selected were chosen such that it effectively compensates for power factor values between 0.7 which is the assumed minimum to as high as 1. From table 4, the lowest capacitance is approximately 7mF while the highest is approximately 79mF hence the steps will be chosen such that these values are closely accommodated. The values chosen are: C1 = 40 mF, C2 = 20 mF, C3 = 10 mF and C4 = 5 mF

Table 5: possible switching sequence of the four step capacitors.

S/NO	C1 = 40 MF	C2 = 20 MF	C3 = 10 MF	C4 = 5 MF	TOTAL
1	0	0	0	0	0 mF
2	0	0	0	1	5 mF
3	0	0	1	0	10 mF
4	0	0	1	1	15 mF
5	0	1	0	0	20 mF
6	0	1	0	1	25 mF
7	0	1	1	0	30 mF
8	0	1	1	1	35 mF
9	1	0	0	0	40 mF
10	1	0	0	1	45 mF
11	1	0	1	0	50 mF
12	1	0	1	1	55 mF
13	1	1	0	0	60 mF
14	1	1	0	1	65 mF
15	1	1	1	0	70 mF
16	1	1	1	1	75 mF

The different combinations of capacitors and the total values for every arrangement is given in table 5.

IV. SIMULATION AND BLOCK DIAGRAMS

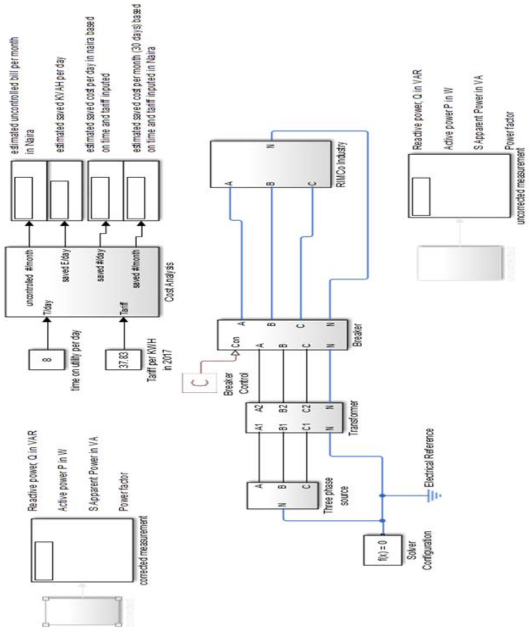

Figure 2. Simulation Block Diagram

The simulation done on the Simulink platform of MATLAB version 2016 is shown here with explanation of each section

The main circuit diagram simulated on the Simulink platform of MATLAB is a 33 KV three phase block is the source of the supply. This source is stepped down by the transformers to 415V. The output of the transformer is then passed through a three phase 415 breaker as was observed in the industry. As seen in the figure, after the breaker the power goes to the industrial load. This load is made up of 7 sections as shown in table 4. Each section was simulated as an RL series circuit. The compensating capacitors are then connected across the load of each section with the automatic controller. A 2000/5A CT is connected in series with one of the phases to measure the current of the load. The load of the industry was almost balanced hence the current from a single phase would be almost equal to that of the other three phases. The design parameters without compensation and with compensation are shown on the displays in the diagram Figure 2. A cost analysis was also done to estimate the amount saved due to the addition of the compensating capacitors using the tariff of EEDC in Enugu state for three phase industrial consumers. The connection of the individual section of the industry to the source of power and to the automatic capacitor selector for compensation is shown in Fig 2.

V. SIMULATION RESULTS AND ANALYSIS

The results for the model of figure 2 is shown here. The results are first taken when the industry is on full load, hence all the machines are operational then simulated again when the industry is operating at 9% of its installed capacity and the cost analysis done for this percentage of load.

When the industry is operating on full load, the resistance and inductance for each section have been calculated as seen in table 1 per phase respectively. These are the values which were used for the full load simulation and the results as shown and explained below.

The simulation model can be seen to give close values to the real-life values shown in table 2. When the active, reactive and apparent power for all the sections are added up, the total active, reactive and apparent power is gotten as

$$\begin{aligned} P_{\text{total}} &= (392 + 184 + 177.4 + 103.6 + 817.3 \\ &\quad + 116.6 + 70.92)e^3 \\ &= 1861.82 \text{ KW} \end{aligned}$$

$$\begin{aligned} Q_{\text{total}} &= (354 + 166.6 + 160.1 + 93.54 + 737.6 \\ &\quad + 105.3 + 70.4)e^3 \\ &= 1687.54 \text{ KVAR} \end{aligned}$$

$$\begin{aligned} S &= (528.2 + 248.6 + 238.9 + 139.6 + 1101 \\ &\quad + 157.1 + 99.93)e^3 \\ &= 2513.33\text{KVA} \end{aligned}$$

When compared to the industrial values as seen in table 2, it is seen that the simulation total power is almost equal to the values gotten in the industry before compensating capacitors are connected.

When the compensating capacitors are in circuit, the total active and reactive power of the system improved as can be seen in fig 4 and 5

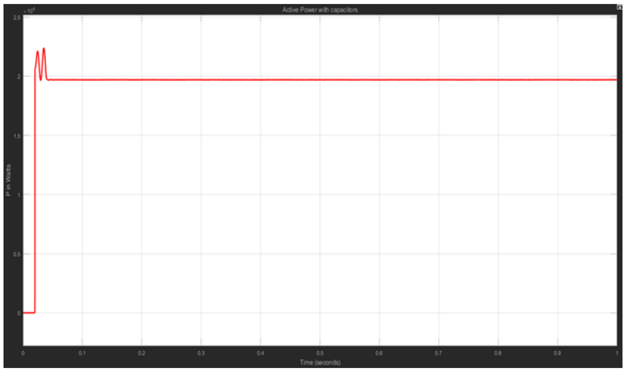

Figure 4: Total Active power with capacitors in circuit

When the compensating capacitors are in circuit, the total active power of the system is seen to be almost 1.9 x 10^5 (190 KW) which is almost same as before the capacitors gotten above as 1861.2 KW. This is because capacitors are reactive and hence do not consume active power. However, there is a slight negligible increase in the active power and this is due to the internal discharge resistance of the capacitor and other losses.

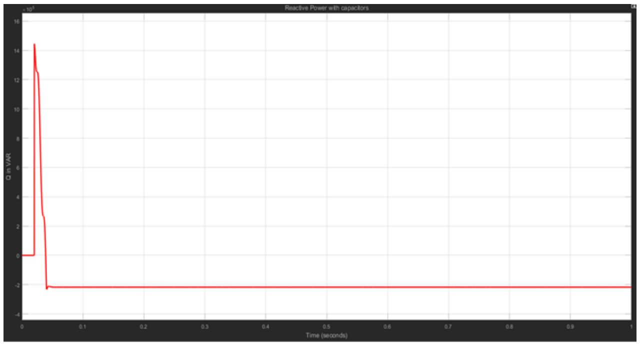

Figure 5: Total Reactive power with capacitors

As seen in figure 5 above, the total reactive power when the capacitors are in circuit is about 2 x 10 ^{5} VAR (200 KVAR) which shows a significant difference from the reactive power when the capacitance was not in circuit. The reactive power is seen to decrease with the addition of the compensating capacitors from about 1687 KVAR when there were no compensating capacitor to 200 KVAR with addition of compensating capacitors. The negative sign only serves to show that the reactive power is inductive.

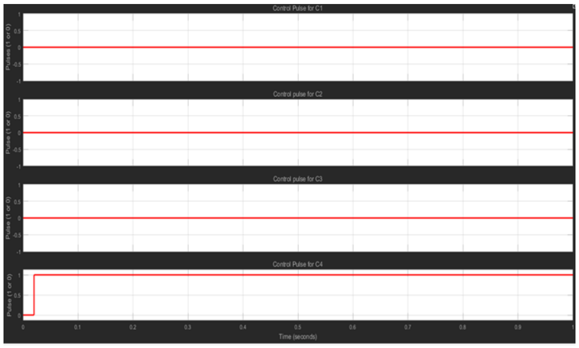

Figure 6: Switching Sequence for the capacitors of solvent plant, new boiler, old boiler, PK mill expeller, and PK mill central panel and workshop machines

From figure 6, it may be observed that the switching sequence gotten by the controller is '0001'. This means capacitor C1 of 40 mF is off or not in circuit, capacitor C2 of 20 mF is not in circuit, capacitor C3 of 10 mF is not in circuit while capacitor C4 of 5 mF is in circuit. The switching sequence seen here corresponds to the 1st output of table 5

Figure 7: switching pattern of capacitors for PK mill expeller motor section

From figure 7, the PK mill expeller section of the case study has a switching sequence of '0010'. This means capacitor C1 of 40 mF is off or not in circuit, capacitor C2 of 20 mF is not in circuit, capacitor C3 of 10 mF is in circuit while capacitor C4 of 5 mF is not in circuit.

Table 6: simulation results before and after compensation for full load

S/no	Parameter	Uncorrected measurements	Corrected measurements
1	Total Reactive Power , Q	1687 KVAR	222.4 KVAR
2	Total Active Power, P	1863 KW	1985 KW
3	Total Apparent power, S	2513 KVA	1997 KVA
4	Power Factor	0.7377	0.9938

Table 6, shows a comparison of the result of the power consumption of the industry under study. The uncorrected measurements show the parameters of the load alone without the compensating capacitors while the corrected measurements show the parameters of the entire system with the compensating capacitors. As seen, when the capacitors are connected across the load, the power factor of the system is improved from 0.7377 to 0.9938. The capacitors in circuit also brings down the reactive power from 1687 KVAR to as low as 222.4 KVAR with a little increase in the active power. The little increase in the active power is mostly due to the discharge resistors connected across the capacitors which consume some active energy when in circuit.

Hence for the entire industry, since each section is connected in parallel to each other as well as their compensating capacitors, to achieve the power factor of 0.9938 seen here, the total capacitance connected across the factory is given as

$$C_{total} = (5 + 5 + 5 + 5 + +10 + 5 + 5)mF = 40mF$$

From the cost analysis of the industry, if it is assumed that the industry runs on this supply for 8 hours every day, using the published tariff scale of 2017 for EEDC the tariff per Kwh for three phase industrial consumers is N37.83. Then by calculations, the industry would be saving about 991.4 KVAh every day which amounts to saving about N9, 001,166 (approximately 9 million

Naira) every month (30 days). Also without a compensator, the industry pays a utility bill of N16, 428,395 (approximately 16.4 million Naira) every month which means as high as 56.25% of the utility bill would be saved for a power factor of 0.74 compensated to a value of 0.994.

VI. SIMULATION RESULTS ANALYSIS

The graph and results above show that the simulated model adequately and constantly monitored the reactive power of the case study industry and switched in the right capacitance in steps to neutralize the reactive power and bring the operational power factor of the industry to almost unity. The programmed controller was able to check the reactive system at every instant, compute the capacitance required to bring the reactive power to a minimum and then produce a switching sequence for the capacitor banks that will produce a capacitance close to the calculated value.

The produced switching sequence was seen to control the switching in of the capacitors and efficiently manage the reactive power of the system bringing it to a very minimal value hence greatly improving the power factor of the industry. The active power of the industry was slightly increased as a result of the addition of the compensating capacitors mainly due to the discharge resistors connected across the capacitors. However, this increase can be considered negligible as seen in the results as the increase was very slight.

The cost analysis which was done showed that by using a compensating circuit as the one designed and simulated in this work, the case study industry would experience significant savings on their electric bill to the tune of about N9,000,000 (9 million Naira) per month when they run for just 8 hours per day. This is equivalent to almost a 55% saving on the utility bill of the industry. This amount saved per month by the use of the compensators and assuming unity power factor supply already covers the cost of materials which would be used in the construction of the compensators. This shows that the use of an automatic power factor controller in the case study industry would be a great advantage to the industry as they would then be operating at a power factor unity. This would reduce the current of the machines as seen in the graph of figure 4.3 hence increasing the life span and reducing wear and tear of the moving parts. Also, the harmonics would be greatly reduced as a result of the good power factor hence reducing vibrations on the machines and by extension increasing the productivity. Most obviously is the reduction in the metered power consumed by the industry which would translate to lower electricity billing by the utility companies and increase the profit of the case study. The cost of employing this device has also been seen by the cost analysis to be relatively cheap as the cost of materials is not up to the amount saved in one month by the use of the compensator.

VII. RECOMMENDATION

This work designed and simulated an automatic power factor correcting circuit. Further study can be done on the use of higher programming techniques such as fuzzy logic and PLC controllers to automatically control the switching steps which will reduce the complexity of the entire circuit. Also, further research can be done on application of this circuit to larger scale areas such as in the Nigerian Power grid which is known to have a lot of transmission losses as a result of poor power factor management and correction from the generating and transmitting centers. Achieving this would greatly improve the power supply to the industries and hence reduce the size and complexity of power factor correction equipment needed at the industrial site.

VIII. CONCLUSION

In this work, an efficient automatic power factor controller for varying industrial inductive loads ,was modeled and simulated on the MATLAB/Simulink 2016 CAD tool. The automatic circuit was achieved using a basic AT89c51 (Atmel 8051) microcontroller to switch in the capacitance such that at every instant, the capacitance in circuit always cancels out the inductive power of the industry bringing the power factor to almost unity. The circuit had 4 capacitance steps of 40mf, 20mf, 10mf and 5mf giving 16 possible combinations or capacitance values. These capacitor steps were carefully selected so that there is a combination for every possible load value to bring the power factor to greater than 0.96. The designed circuit was seen to be very efficient as it greatly improved the power factor of the system irrespective of the load to almost unity as seen in the simulation graphs and was able to achieve a 55% reduction in the electricity billing of the case study. Power factor correction is seen to be of utmost importance as it leads to a great reduction in the metered power (VA) of the industry thereby reducing the utility billing per month as seen in the cost analysis of the work.

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