HIGH VOLTAGE CAPACITOR BANK WITH PLC BASED AUTOMATIC PF CONTROLLER FOR ELECTRIC ARC FURNACE APPLICATION

[1]Nair Nandkumar, [2]Saju S B, [3]Nisha K B

[1]Senior Associate Vice President, [2]Deputy Manager, [3]Deputy Manager,
[1]Manufacturing & Projects,
[1]Carborundum Universal Limited, Kochi, India.

Abstract : Low Voltage Capacitor banks for reactive power compensation are well established. However, use of High Voltage capacitor banks for VAR compensation is not used as extensively by industries & utilities due to various complexities. For certain specific industries using Electric Arc Furnaces, the LT capacitor bank compensation would not yield the intended benefit as the high inductive load is contributed by the Arc Furnace transformer & reactor on the High Voltage side. Conventional HV Capacitor Bank with automatic power controller relay may not be the right solution for such applications. This paper discusses the challenges and issues faced in VAR compensation for a factory using multiple Electric Arc Furnaces with highly fluctuating load pattern. A capacitor bank with PLC system for automatic regulation has been implemented for achieving near unity power factor.

Index Terms - **Electric Arc Furnaces (EAF), power factor, PLC, harmonics.**

I. INTRODUCTION

Electric Arc Furnaces (EAF) are designed and used for melting, smelting and refining applications of metals and non-metals. Often, in factories equipped with Electric Arc Furnaces, the EAF contribute to single largest individual load. In many non-metal fusion applications, the size of EAF are comparatively smaller in capacities but such factories are characterized by having several EAFs in operation in same production facility.

Operation of a single large EAF or multiple smaller sized EAFs in same premises can contribute to non-linear loads due to the Voltage-Current characteristic of the Arc furnace. The Electrical system design should be robust enough to ensure that the waveform distortions, voltage unbalances and voltage fluctuations caused by EAFs does not affect the other users. For this reason, facilities using EAF generally have EHT substation which steps down the Extra High Voltage to High Voltage needed for the operation of EAF.

The Power factor of operation for EAFs are generally in range of 0.70 to 0.95 depending on the furnace design as well as by the product undergoing the fusion process. Industries operating with power factor lower than 0.95 are disadvantaged due to Two Part Tariff charged by Utilities. Most electric utilities in India also impose penalties for operation with lower power factor. Some utilities also provide incentives for operation with high power factor.

For industries equipped with several small EAFs in same premises, use of static VAR compensation may not be the most economical solution to improve the power factor. A more economical solution would be to provide high voltage capacitor banks for power factor compensation.

II. CHALLENGES POSED BY ELECTRIC ARC FURNACE IN POWER SYSTEM

Most Electric Arc Furnaces operate with the furnace transformer connected in series with a reactor for obtaining arc stability. The reactor windings are either stand-alone units or are provided inside the transformer itself. Both, the furnace transformer as well as the reactors have separate On Load Tap Changers (OLTC) which enables online changing of tap during the course of furnace operation. The inductance of the transformer and reactor windings contribute to lower power factor of the system.

EAF operation causes voltage flicker, randomly fluctuating currents, harmonics and lower power factor of the system. Provision of a capacitor bank with automatic Power Factor Controller (PFC) relay can lead to rapid & frequent switching ON & OFF of the banks resulting in generation of undesirable harmonics and thereby create a detrimental impact on the power quality. More-over, frequent switching-on and switching-off of capacitor banks will also lead to premature failure of the capacitors.

The complexities increase many fold when there are different capacity furnaces which are Switched-On and Switched-Off at different time zones. The design would generally need a very large capacitor bank to obtain a unity power factor to eliminate excessive frequent switching in and out of same bank if conventional PFC relays are used.

III. PROBLEMS WITH CAPACITOR IN SYSTEM RESONANCE

Capacitors do not produce harmonics but, their use in EAF circuits can aggravate power quality issues due to frequent switching and resonance. If harmonics is present above permissible limits, the impact will be on premature failure of capacitors. Frequent blowing of capacitor fuses is indicative of such a system aberration which will eventually lead to capacitor failure if left unattended. When fuses blow in a capacitor bank, the parallel resonant frequency will shift. The system will therefore de-tune itself, shifting the parallel resonant point to a higher frequency, perhaps resulting in a stable operating condition. Problems could re-occur when the blown fuses are replaced, thereby re-tuning the system to the original parallel resonant frequency which caused the initial fuse blowing

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IV. DESIGN CONSIDERATION WITH MULTIPLE SMALL EAFS

Figure-1 shows single Line diagram of a 66/11 kV, 24 MVA Substation with 10 numbers of Electric Arc Furnaces connected to the 11 kV circuit. The furnaces are started and stopped at different time zones depending on the operational requirements of the production.

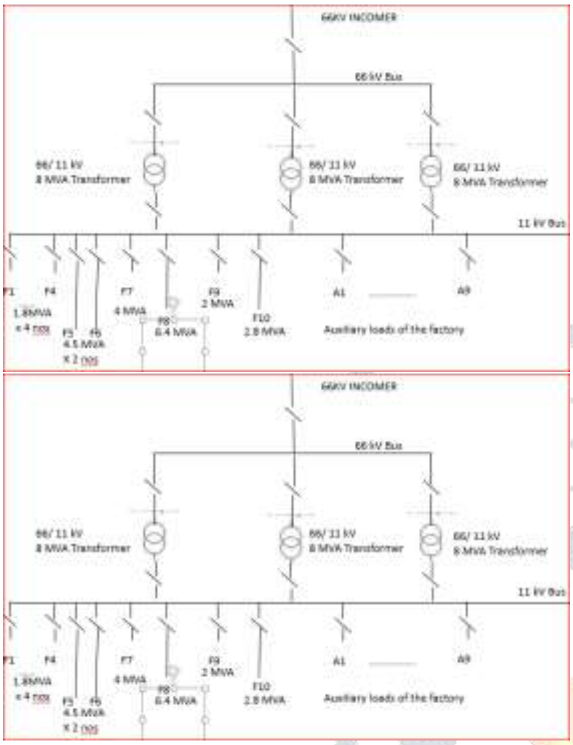


Figure 1 Single Line Diagram of EAF power circuit

Table-1 provides the data of furnace ratings with various operating modes. This kind of operating configuration create complexities in the HV Capacitor design apart from the challenges already posed by the inherent nature of EAF loads.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
MVA	1.8	1.8	1.8	1.8	4.5	4.5	4	6.4	2	2.8
M1	√	√	√	Off	√	Off	√	√	√	√
M2	Off	Off	Off	Off	√	√	√	√	√	√
M3	√	Off	Off	Off	√	Off	√	Off	√	Off
M4	√	√	Off	√	Off		√	√	√	√
M5	√	Off	Off	Off	Off	Off	√	Off	Off	Off

Table 1: Furnace operation mode ; M1 to M5- Different Mode of operation; F1 to F10- Furnace

Key objective to be fulfilled is to improve the system power factor to near unity by automatic switching of the bank under various load conditions.

Power parameters were monitored for various configurations shown in Table 1 M1 to M5 using online power meter. The maximum condition of loading happens under the operation mode M1 refereed in Table 1: Base load condition of F1, F2, F3, F5, F7, F9, F10 in operation and (6.4 MVA) F8 switched on.

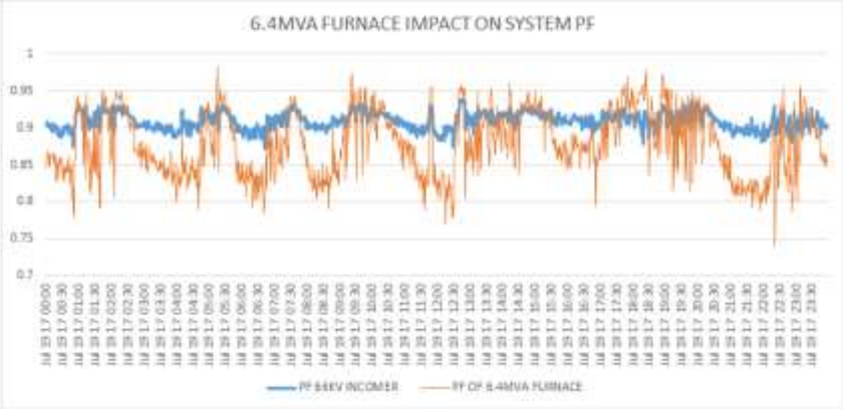
Other design considerations are:

- To ensure that same bank should not frequently switch On & OFF. A time delay has to be provided to ensure minimum required discharge time for capacitors.
- Design should be Modular to facilitate future addition of capacitors to increase the MVAR rating. Figure 1 shows the basic layout of a 11 kV capacitor bank

V. CAPACITOR & REACTOR SIZING

The existing system voltages, current fluctuations and power factor variations were studied over different time periods for the furnace operating configurations.

Graph 1 depicts the trend chart of PF variation on 66 kV due to PF variation contributed by the operation of 6.4 MVA EAF.



Graph 1: Impact of 6.4 MVA, 11 kV EAF operation on overall system PF at 66 Kv

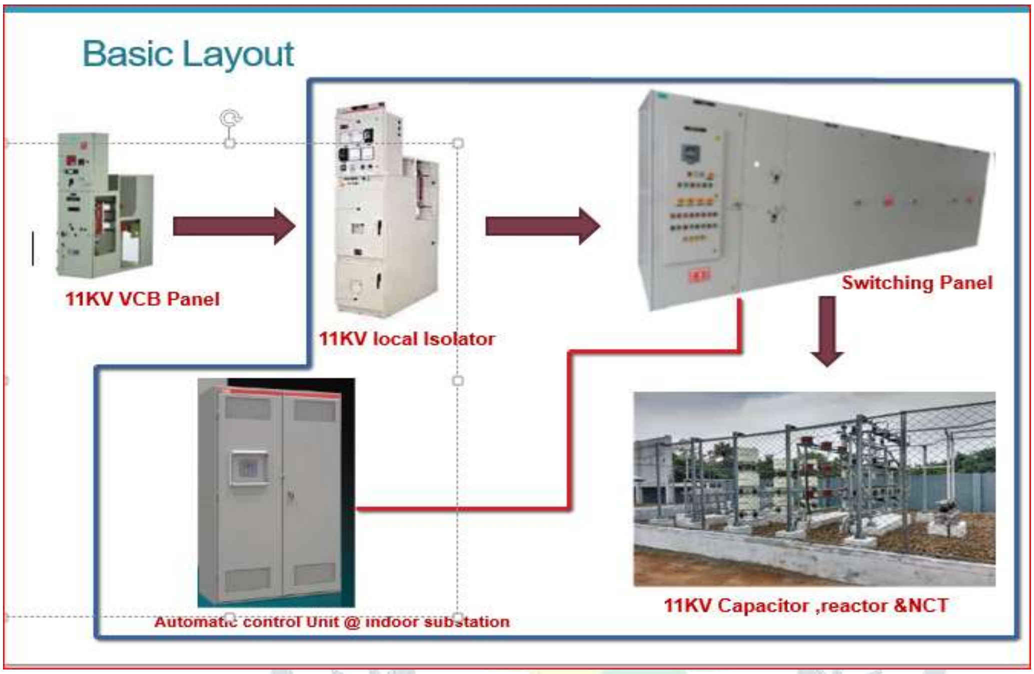


Figure 2: Basic layout of 5 MVAR Capacitor bank

Based on the continuous monitoring of the 66 kV Bus electrical parameters, the highest MW and MVA loading as well as the power factor under such highest loading were noted as shown in Table 2.

Parameter	Value	Units
Active Power	16523.70	kW
Apparent Power	19998.30	kVA
Reactive Power	9773.30	kVAR
Power Factor	0.81	

Table 2: Highest recorded Power data

Observation 66kv incomer							
Parameters	MIN	MAX	AVG	Parameters	MIN	MAX	AVG
Vrms L1-2	60.55	61.75	61.23	KVAR Line1	1170	3257.67	1713.9
Vrms L2-3	60.8	62.01	61.5	KVAR Line2	860	3201.00	1265.38
Vrms L3-1	60.88	62.31	61.76	KVAR Line3	860	3315.00	1383.7
Arms Line1	99.04	170.1	126.16	KVAR Sum	3270	9773.00	4327.98
Arms Line2	92.7	175.2	118.19	KVA Line1	**3500**	6506.00	4462.77
Arms Line3	100.2	172.1	128.77	KVA Line2	3280	6720.00	4188.14
Vthd Line1	0.78	0.99	0.89	KVA Line3	3600	6766.00	4627.03
Vthd Line2	0.72	0.91	0.82	KVA sum	10620	19998.00	13279.37
Vthd Line3	0.64	0.86	0.74	KW Line1	**3270**	**5507.67**	4116.19
Athd Line 1	1.74	4.27	2.87	KW Line2	3160	5557.00	3989.32
Athd Line 2	1.55	4.35	2.68	KW Line3	3480	5457.00	4414.33
Athd Line 3	1.6	4.6	2.62	KW Sum	10070	16523.00	12500.04
Power factor	0.81	0.96	0.92				

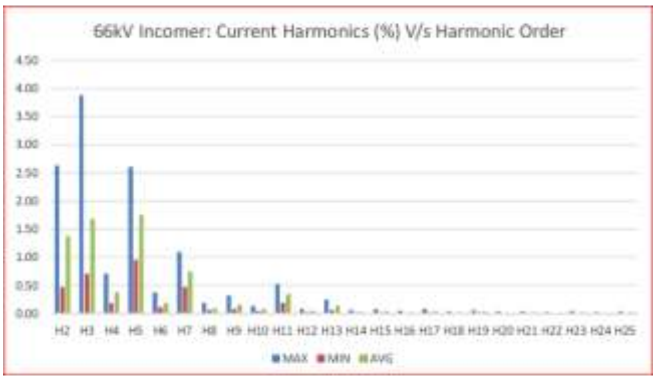
Table 3: Power data summary with Harmonics measurement at 66 kV

The curent trends were monitored as shown in Graph 2 while graph 3 provides the Power variation trend under peak loading conditions.

Graph 2 : Current trend chart on 66 kV bus for stabilised operating condition of plant

Graph 3: Power consumption trend under peak loading condition of plant

Graph 4: Power factor trend under normal loading condition of plant



Graph 5: Plant current harmonic spectrum

The transformers in the circuit in combination [three numbers of 8 MVA power transformers with ten numbers of furnace transformers and nine auxiliary transformers] together contribute a system impedance of 1.3 ohm and major harmonics in 3^{rd} harmonic range. So reactor for offsetting the impact of 3^{rd} harmonics has to be provided along with the capacitor bank.

Based on above studies, VAR compensation of 5 MVAR capacity with three steps as shown in Table 4 was designed. Table 5 provides the recatance values for neutralizing the 3rd harmonics in the system to protect the capacitors.

Parameter	Step 1	Step 2	Step 3
Installed Capacity			
kV	12.65	12.65	12.65
MVAR	1.53	3.06	3.06
Effective Capacity			
kV	11	11	11
MVAR	1	2	2

Table 4 Proposed Capacitor Bank

Parameter	Step 1	Step 2	Step 3
Reactor Rating			
Current	63.80 A	127.60 A	126.60 A
Inductance	61.233 mH	30.616 mH	30./616 mH

Table 5 Reactance rating for Capacitor Bank

The capacitor voltage specification is taken as 12.65 kV considering 15% continuous over-voltage in the system and to compensate for the drop because of harmonic currents flowing in the bank

The MVAR rating of the capacitor is chosen at higher than required to compensate the reactance provided in the circuit which works out to 13.4% of capacitance value.

Verification of Reactor design

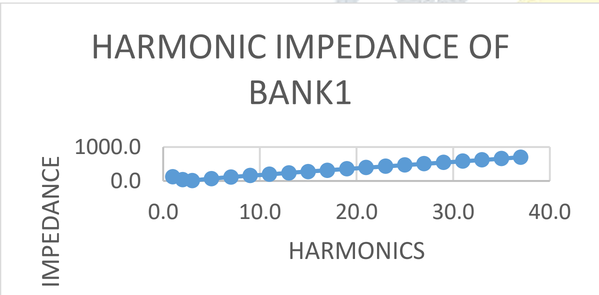
For step 1:

Xc=140.46 ohm and X_L=19 ohm

Impedance value at 2.71 = 0.

Hence confirmed that system tuned at 2.71.

Reactors of 13.72% with a tuning factor of 2.7 are selected based on the simulations done.



Graph 6: Harmonic impedance of bank1

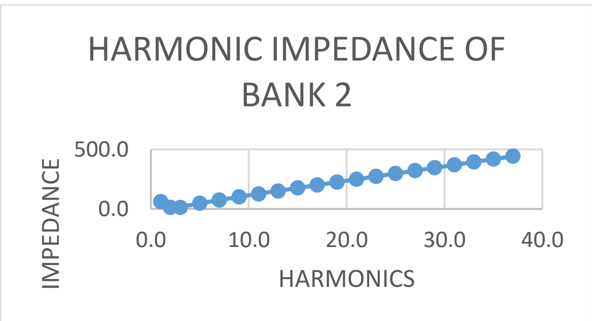
For Step 2 & 3 :

Xc=70.23 ohm and X_L=9.613 ohm

Impedance value at 2.71 = 0.

Hence confirmed that system tuned at 2.71.

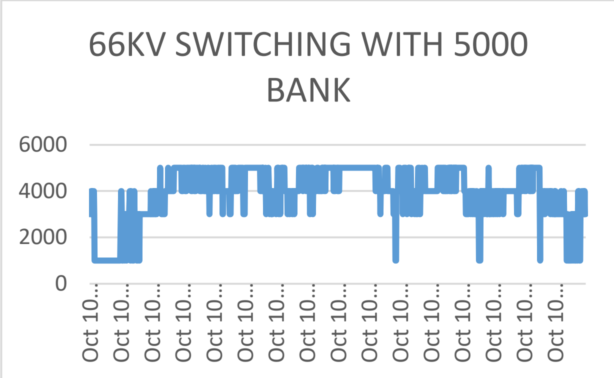
Reactors of 13.72% with a tuning factor of 2.7 are selected based on the simulations done.



Graph 7: Harmonic impedance of bank 2& 3

At 3rd harmonics system impedance would be less than 4.15 ohm and bank impedance would be 12.6 ohm

VI. PARAMETERS AFTER INSTALLATION OF 11KV 5 MVAR BANK 3 STAGE WITH PLC CONTROLLER

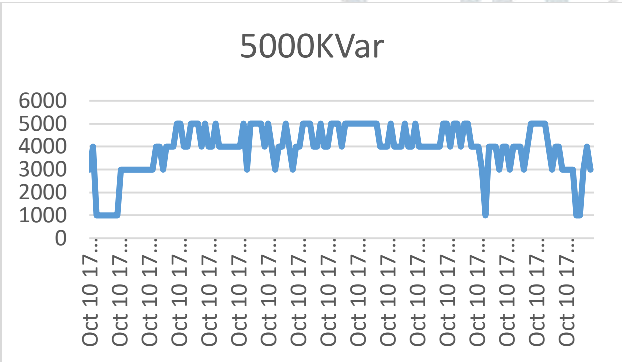


Graph 8: Normal controller switch cycle

To ensure stable operation of capacitor bank without frequent switching, a customised algorithm based on the various modes of EFA operation was developed instead of using a conventional Automatic Power factor controller.

Graph 8 depicts the bank operation with a conventional automatic power factor controller relay while Graph 9 is the operation of the system with PLC based automatic PF controller. A more stable operation providing for 10 minute discharge time of capacitor is provided between ON & OFF cycle of individual capacitors.

The switching logic similar to one shown in Table 5 is developed for the purpose.



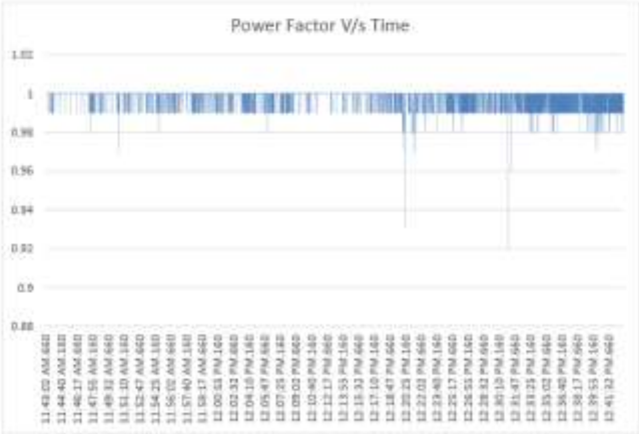
Graph 8: Switching with PLC controller

Table 5 switching logic of PLC

VII. RESULT

PF compensation achieved after installation of the 5 MVAR capacitor bank with PLC controlled automatic PF regulation is near unity as shown in Graph 9.

The harmonics in the power system were measured before and after installation of the detuned 5 mVAR capacitor bank. As shown in Table 6, there is power quality improvement after the installation of the capacitor bank. The most significant being the improbvement of PF form 0.93 to unity.



Graph 9: PF at EHT side with capacitor in line

Feeder	Parameters	With Cap	Without Cap
66kV Incomer	THDV	1.03	1.11
	THDI	2.9	3.44
	PF	1	0.93

Table 6 Harmonic analysis summary with VAR compensation

VIII. Conclusions

A detuned 3 stage 5 MVAR 11 kV capacitor bank with PLC based automatic power factor controller was designed and installed for a 24 MVA substation having 10 EAFS of different capacities. The system power factor improved from 0.93 to 0.995 with installation of the bank. The performance of the system has been monitored for past 24 months and found to be satisfactory. The authors recommend use of capacitor bank in combination with reactors of appropriate design to offset harmonics for improving the power factor of installations having EAFs .

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