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Power Factor Improvement of Industrial Loads using a Capacitor Bank and a Solar PV System

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***Abstract*—A significant portion of the cost of manufacturing in the industry is related to electrical power. An electrical system with a low power factor is typically less effective and may also be less profitable for end users and system operators. Therefore, power factor correction is essential for effective system performance and for lowering the cost of electricity. This paper presents a study on the technical and financial benefits of power factor improvement, which is supported by a real-world industrial load with a combination of a capacitor bank and a solar photovoltaic system. A load flow software is used to model and analyse the electrical system of the site with the dynamic loads. The capacitor bank's connected duration is calculated by keeping track of the power factor, active power, and reactive power values during the day. The capacitor bank is sized to meet the reactive power needed at night. By examining the 24-hour solar irradiance data at the location, the solar system is designed to meet the peak active power consumption of the site. The voltage source converter coupled to the solar system is adjusted to produce the reactive power required to maintain the power factor during the day. The findings demonstrate that the suggested 40 kvar capacitor bank and 553 kW solar system successfully increase power factor by 39%. A simple payback period for the suggested system is six years, and it also results in monthly savings of 905806 LKR.**

***Keywords*— Capacitor Bank, Power Factor Improvement, Reactive power, Solar Photovoltaic System, Voltage Source Converter**

I. INTRODUCTION

Power quality refers to the efficiency of the electrical grid in supplying power to customers and the capability of the equipment to use the supplied power. High power quality is indicated by a power factor closer to one. A lower power factor worsens the power quality and increases the cost of electricity. There are three basic types of consumers in Sri Lanka; 1)Domestic, 2) Industrial, and 3)Commercial. Any industrial process relies heavily on the quality of the electrical power, which is vital in terms of economic and technological advantages [1]–[4].

In contrast to residential loads, most commercial and industrial buildings have high inductive loads, such as electric motors, ventilation, refrigeration, air conditioning, and fluorescent lighting. The power supply is distorted, and the power factor is reduced due to these installations and their functioning. A plant with a poor power factor experiences significant losses, and it can cause a thermal problem in the switchgear and a negative impact on the cost of electricity, energy waste, and the lifespan of the electrical equipment. On the other hand, a low power factor results in a higher electricity bill for an end user for the same amount of active power [3].

Therefore, finding the most cost-effective strategy for improving the power factor for industrial power users is critical. The literature contains reports of numerous studies on power factor improvement [5]–[10]. Theoretically and economically, corrective measures, including installing shunt capacitor banks and using onsite synchronous machines to supply reactive power locally, were examined [8]–[10]. The size of the capacitor bank is determined by the type of electrical load in the plant [11]. Three strategies such as individual compensation, group compensation, and central compensation, were suggested for locating the capacitors [11], [12]. By employing various energy-saving techniques, industrial plants can reduce their overall energy use. Demand-Side Management techniques (DSM) assist industrial users in lowering production costs and increasing market competition. Through conservation measures and demand efficiency, DSM techniques assist consumers in lowering their energy consumption expenses [13]. Distributed energy resources based on solar PV are one such method of DSM techniques

In summary, most conventional power factor improvement methods are based on capacitor bank installations [10]–[12]. They have been able to improve the power factor. However, the flexibility of controlling the capacitor bank to regulate the power factor is lower and can result in over and under-correction of the power factor. Also, the capacitor bank alone cannot lower the electricity bill of industrial loads. Thus, it is necessary to introduce a technique to regulate the power factor of industrial loads while minimizing the electricity charges(for kWh consumption). Therefore, this paper explains an investigation on improving the power factor by combining a capacitor bank and solar panels in a garment factory in Sri Lanka named ”Miami Exports (Pvt) Ltd” with the goal of minimizing maximum demand and electricity cost by modeling and analyzing the company's electrical system and observing the electricity usage. Section II discusses the overview of the factory, and section III explains the details of system modeling and demand analysis. Power factor correction methods proposed for the factory are explained in Section IV. Next, section V presents the results and discussion, and finally, section VI concludes the paper.

II. OVERVIEW OF THE FACTORY

Miami Exports is a leading manufacturer of BAM Holdings, a Sri Lankan corporation with various commercial interests in the garment industry, founded in 1980. It specializes in the production and export of children's clothing. Miami Exports has several sub-factories, and the factory in Ranna, in the southern province of Sri Lanka, is selected to conduct the research. Fig.1 shows the basic layout of the company.

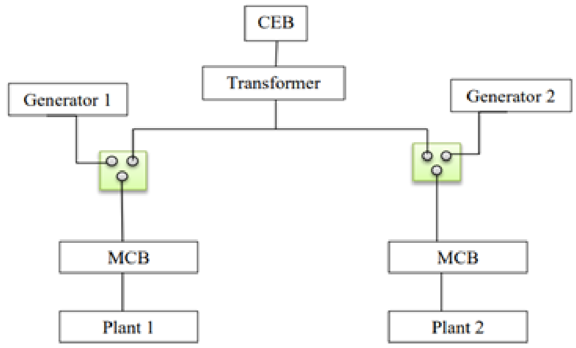

Fig. 1. The basic layout of the factory

The factory has two plants, namely, Plant one and Plant two. It takes electricity from the Ceylon Electricity Board(CEB) through a 630kVA transformer. In case of a power cut, plant one is powered by a 500 kVA generator, while plant two is powered by a 250 kVA generator. Plants one and two take the electricity through the changeover switches separately.

Mainly, plant one has fabric stores, an inspection section, a sewing Department, an ironing section, a packing section, and a finishing section. The basic layout of plant one is given in Fig.2. The cutting section and the canteen are common for both plants one and two. The sewing Department has a new production area, and production lines one, two, and three. The cutting building has three floors. The ground and first floors are used for the cutting section, and the second floor is used for the fabric stores and inspection. The cutting section has two auto-cutter machines with 15 kW induction motors.

Other than that, it has fusing machines and spreader machines. Exhaust fans with 0.5 HP induction motors are used in the sewing Department. Most machinery and electrical equipment are sewing machines, most of which are powered by servo motors, while induction motors power others. The ironing section has ironing tables with 0.55 kW induction motors.

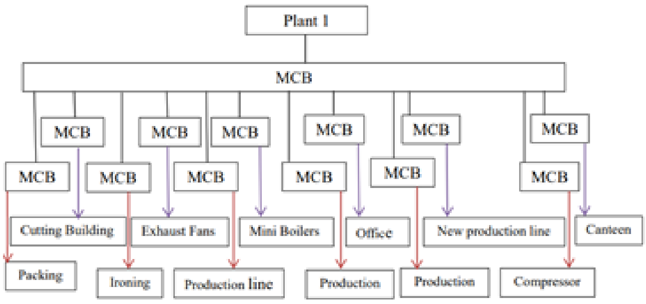

Fig. 2. The basic layout of plant one

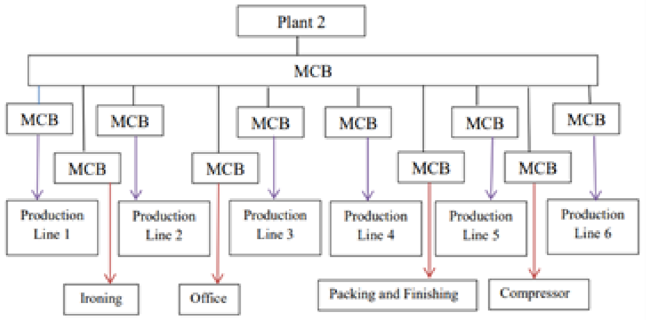

Fig. 3. The basic layout of plant two

The canteen uses two 0.5 kW motors for coconut scraping, two 1.5 kW hot water boilers, and four fridges. The air compressor unit consists of two 75 kW induction motors and a 30 kW induction motor to provide compressed air for machines.

Mainly plant two has fabric stores, an inspection section, a sewing section, an ironing section, a packing section, and a finishing section. The sewing Department has six production lines, and each has fifty servo motors. Each fabric and inspection section has three 0.5 HP induction motors.

TABLE I. SECTION-WISE ELECTRICAL APPLIANCES

Section	Machines	Number of Machines	
		Plant 1	***Plant 2***
Fabric Stores	Exhaust fan	-	2
Fabric Inspection	Fabric Inspection machine	1	1
Cutting	Auto cutter machine	2	-
	Spreader machine	3	-
	Plotter machine	2	-
	Fusing machine	2	-
	AC machine(Split)	2	-
Sewing Department	Sewing machine	300	280
	Heat seal machine	4	4
	AC machine(Split)	10	6
	Air compressor	2	2
	Mini boiler	5	5
	Bottle iron	10	8
	Exhaust fan	24	-
Ironing	Steam boiler(Fuel)	1	1
	Exhaust fan	-	1
	Iron table	38	19
	Industrial standing fan	-	3
Packing	Threat sucker machine	1	2
	Metal detector machine	1	1
	Exhaust fan	-	1
Canteen	Coconut scraping machine	2	-
	Hot water boiler	2	-
	Fridge	4	-

TABLE II. CAPACITY OF ELECTRICAL APPLIANCES

Load	Rating (kW)
Exhaust fan	0.4
Auto cutter machine	15
Spreader machine	0.15
Plotter machine	0.25
Fusing machine	3.5
Sewing machine	0.5
Heat seal machine	2
Air compressor	75
	30

Load	Rating (kW)
Mini boiler	6
Bottle iron	1
Iron table	0.55
Industrial standing fan	0.15
Threat sucker machine	3
Metal detector machine	0.15
Coconut scraping machine	0.5
Hot water boiler	1.5
Fridge	1.5

The ironing section has nineteen ironing tables with 0.55 kW induction motors. Two compressors (75kW and 30kW) are used to provide compressed air for machines. The basic layout diagram of plant two is illustrated in Fig. 2. Section-wise electrical appliances in plants one and two and their capacities are listed in Tables I and II, respectively.

The Ceylon Electricity Board in Sri Lanka provides electricity to the company under industrial II customer category tariff structure. Reactive power demand is currently billed based on the maximum demand in kilovolt amps (kVA) for each calendar month, which is around 500000 LKR every month.

III. Demand Analysis of the Factory

A load flow software is used to model and analyze electrical system. Power factor, active power, reactive power, and electrical demand are observed under different load percentages of the machines in the company. The model is simulated under various overall load percentages from 40% to 100% when all loads are connected. The variation of active power, apparent power, reactive power, and power factor is listed in Table. III.

The average maximum demand of the company calculated from past data is about 452 KVA. It is assumed that at the peak, all the motors in the factory are loaded. So, the loading percentage in accordance with the average maximum demand is calculated. In terms of the modeling results shown in Table.III, demand falls within the range of 40% to 60% loading categories. The peak loading percentage for the plant is therefore calculated to be 50%, at which point the total active and reactive power are 310.5 KW and 330 Kvar, respectively.

In this study, it is assumed that all the motors in operation are loaded at the same percentage of full load throughout the day. Therefore, the percentage found at the peak is used to find the average active and reactive power variation with time as listed in Table. IV.

IV. Power Factor Correction

The incorporation of renewable energy sources can reduce grid energy consumption and also results in a lowering of electricity bills. Solar photovoltaic systems can be simply installed on the roofs of both residential and commercial buildings as grid-connected PV applications. Also, they can provide power without the use of any harmful pollutants and can also generate reactive power levels [14], [15]. Therefore, a solar PV system is used to cater to the daytime demand of the factory while regulating the power factor.

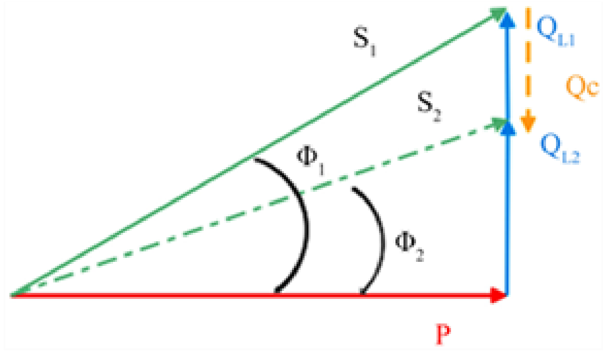

Fig. 4. Power triangle

However, the grid tie solar system gets disconnected during the night when solar power is not available. Therefore, a capacitor bank is proposed to generate the required reactive power at night.

A. Capacitor Bank

A capacitor bank is an arrangement of several capacitors used to add kvar to the electrical system, thereby enhancing the power factor. Shunt capacitor banks are collections of parallel and series-linked elements. The purpose of designing a capacitor bank is to calculate the amount of reactive power needed in the power system to maintain an improved power factor.

Fig. 4 depicts the power triangle used to calculate how much reactive power must be added to the system to achieve the target power factor improvement [16]. The capacitor is sized using (1) and (2) to regulate the power factor at 0.95 at night when the solar system is disconnected from the system.

$$Q = P\ (\tan\theta_1 - \tan\theta_2) \quad (1)$$

$$Q = 3 \times V^2 \times 2\Pi fC \quad (2)$$

TABLE III. The Simulation Details of the Overall Electrical Model

Load category	Active Power (kW)	Apparent Power (kVA)	Reactive Power (kvar)	Power Factor (%)
100%	887.5	1047	555.1	84.78
90%	782	937.5	517	83.41
80%	490.9	609.1	360	80
70%	434.6	561	355	77.4
60%	372.4	509	347	73.08
50%	310.5	452	330	68
40%	248.4	390	300	63

TABLE IV. Power Consumption of the Factory for Different Times of the Day

Time	Load	
	Active Power (kW)	*Reactive Power (kvar)*
7.30 - 8.30	116.9	71.2
8.30 – 9.30	303.5	332.9
9.30 – 10.30	303.5	332.9
10.30 – 11.30	303.5	332.9
11.30 – 12.30	303.5	332.9
12.30 – 13.30	151.1	177.5
13.30 – 14.30	278.7	282.7
14.30 – 15.30	108.5	122.9

Time	Load	
	Active Power (kW)	*Reactive Power (kvar)*
15.30 – 16.30	261.3	278.9
16.30 – 17.30	261.3	278.9
17.30 – 21.30	52.9	56

Where; P = Active power (kW)
Q = Required reactive power (kvar)
θ_1 = Existing power factor angle
θ_2 =Improved power factor angle
V = Per phase operating voltage
f = Operating frequency
C = Per phase capacitance

B. *Solar PV System*

The DC-DC-AC inverter topology, commonly referred to as two-stage power conversion, provided the basis for the design of the solar PV system. The block diagram of the solar PV system is shown in Fig.5. Solar panels are sized to cater the peak demand of the factory in the daytime. The DC/DC converter is placed between the solar PV panels and the voltage source converter to improve voltage gain and energy collecting capability. A maximum power point tracking (MPPT) device is connected with the DC/DC converter to maximize the instantaneous DC power output of the solar PV panel. The MPPT device regulates the DC/DC converter's duty ratio until the solar PV panel's DC supply voltage is attained and maintained at its maximum power point voltage. The voltage source converter generates an AC voltage from a DC voltage.

This study analyzes the controls of the voltage source converter to generate the desired reactive power. Therefore, this article does not present the controls and details of the rest of the system. More details on the grid following inverter-based solar system can be found in [17], [18].

Voltage-source converter (VSC) converts a DC voltage into an AC voltage. The inverter is critical in controlling the solar PV system's active and reactive power. The circuit diagram of the VSC is shown in Fig. 6. The dc side voltage in the converter and the delivered reactive power are regulated with the support of PI controllers, and they are used to generate the reference current for the inner current loops. The generated ac voltage, on the other hand, is connected to the ac system via a low pass filter on the ac side [19].

Certain characteristics of reactive power compensation with voltage source converter (VSC) technology can be favorable to overall system performance. Voltage source converters (VSC) are utilized with series-connected insulated gate bipolar transistors (IGBT). VSC can generate reactive power by the use of freewheeling diodes on each of the power switches.

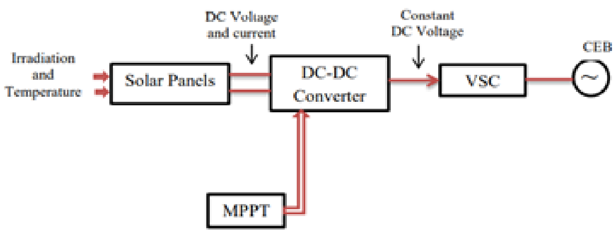

Fig. 5. The block diagram of the solar PV system

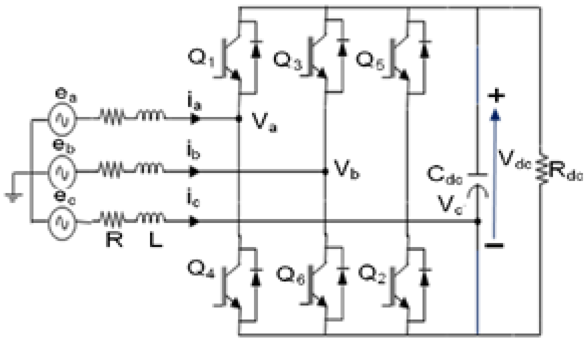

Fig. 6. Circuit diagram of the VSC [20]

Due to the existence of inductive components in the load, poor power factor occurs due to high reactive power. As a result, the current-voltage phase difference increases, and the power factor is reduced. The power triangle shown in Fig. 4 is used to build the blocks in the PSCAD model. Incorporating (1), the amount of reactive power required to inject into the system to maintain the desired power factor improvement of 0.95 is found.

The strategy shown in Fig. 7 is used in the PSCAD software to generate reference reactive power. Grid side active and reactive power values (labeled as PP and QQ) are taken to build the power factor control block. Desired reactive power level to maintain the power factor at 0.95 is calculated. The error between the desired and the actual reactive power values are fed into a PI controller to generate the reference for reactive power loops of the VSC. Also, active power and reactive power change from time to time. According to the power values, the power factor is maintained at 0.95 by using the power factor control block.

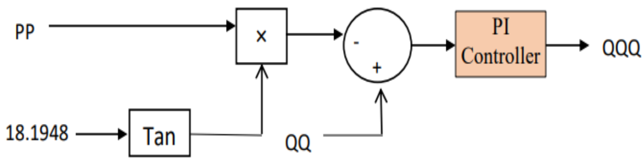

Fig. 7. Power Factor Control Block

V. RESULTS AND DISCUSSION

At around 11 am, the maximum average solar power generated by a 1 kW solar panel is 504.116 W, and at that period, the maximum active power of the factory is observed at around 278.77 kW. Therefore, the combination of the 40 kvar capacitor bank and the 553 kW solar PV system is proposed, and it improves the power factor of the factory from 68% to 95%. Fig. 8 illustrates the improved power factor after the power factor corrections.

Table. V compares the simulation and calculated power flow at the main circuit breaker in all time slots after introducing the power factor improvement methods. Calculated power values are slightly different from the software's simulation result values because of the internal losses in the simulated circuits. The plant is open at 7.30 am, and operations continue until 9.30 pm. From 7.30 am to 5.30 pm, approximately all the sections are operating at their maximum efficiency.

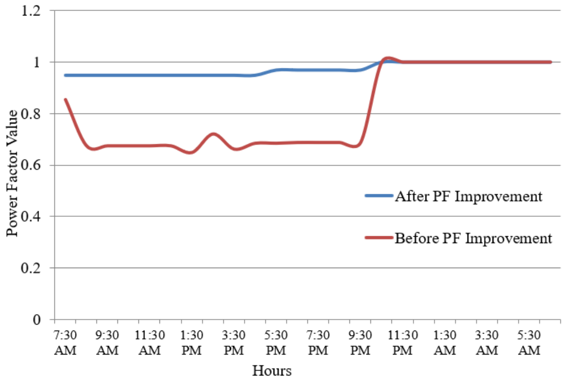

Fig. 8. Power Factor Improvement

TABLE V. COMPARISON OF THE SIMULATION RESULT WITH THE CALCULATED RESULT

Time	Load		Solar Power kW	Calculated		Simulated		PF
	Active power kW	*Reactive Power kVAr*		*Active power kW*	*Reactive Power kVAr*	*Active power kW*	*Reactive Power kVAr*	
7:30-8:30	116.9	71.2	103.63	13.27	3.86	15.12	5.56	0.95
8:30-9:30	303.5	332.9	185.84	177.66	91.66	169.3	88	0.945
9:30-10:30	303.5	332.9	260.9	42.58	33.17	38.53	30	0.946
10:30-11:30	303.5	332.9	275.5	31.99	21.80	29.8	19	0.948
11:30-12:30	303.5	332.9	278.77	27.72	19.26	24.71	17	0.951
12:30-13:30	151.1	177.5	262.26	111.16	96.92	105.2	91.25	0.946
13:30-14:30	278.7	282.7	201.8	76.87	53.16	82.43	56.04	0.953
14:30-15:30	108.5	122.9	159.83	51.34	41.56	46.71	38.51	0.945
15:30-16:30	261.3	278.9	111.49	149.8	102.3	155.5	108.0	0.946
16:30-17:30	261.3	278.9	35.94	225.3	165	229.5	169.1	0.946
17:30-21:30	52.9	56	-	-	-	51.89	16.49	0.96

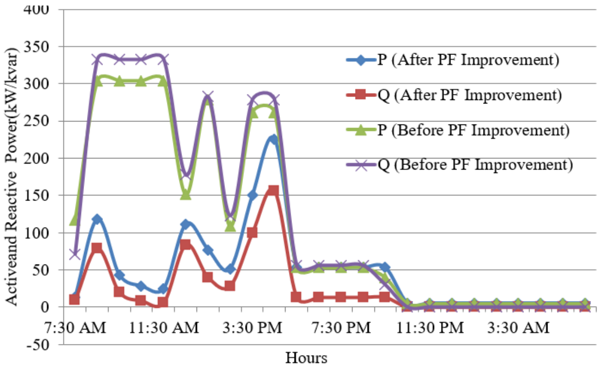

Fig. 9. Active power and Reactive power

At that period, a solar PV system maintains a 95% power factor by providing the required reactive power to the system. From 5.30 pm to 9.30 pm, when the solar system is disconnected from the system, only the packing section of the factory is operated. The required reactive power is low at that time and the capacitor bank improves the power factor up to 97%. After 9.30 pm, every machine is powered off, and only LED security lights are operated until 6.00 am of the next day. During that period, energy consumption is very low, and it is assumed it is zero. Therefore, it is better to switch off the capacitor bank from 9.30 pm to 7.30 am, which can be facilitated by a breaker controlled by a timer connected to a relay.

The integration of renewable energy sources reduces energy consumption from the CEB. The company's typical maximum demand, based on historical data, is around 452 KVA and, after power factor corrections, it reduces to 274 KVA, which is about a 39% reduction. Fig. 9 illustrates the active power and reactive power values after the integration of the capacitor bank and the solar panel.

TABLE VI. COST REDUCTION DETAILS WITH THE POWER FACTOR IMPROVEMENT

Power Factor	Maximum Demand (kVA)	Cost per unit (LKR)	Cost for Maximum Demand (LKR)
0.68	452	1100	497200
0.95	274	1100	301400

Under the industrial consumer II tariff structure, the maximum demand penalty paid by the company to the Ceylon Electricity Board is 1100 LKR per kVA. It accounts for 497,200 LKR each month on average, with a maximum demand of 452 kVA as listed in Table. VI.

Power factor improvement of 0.95 is preferred because it saves more energy and allows for less over-correcting throughout the day when all loads are running. Also, the reactive power consumption of motors is roughly consistent with the load compared to the active power requirement.

The total cost for capacitor bank and solar PV system installation is about 700,000 LKR and 66 360 000 LKR, respectively. The installation can benefit the plant with a monthly saving of 905806 LKR and can result in a payback period of six years.

VI. CONCLUSION

This study presents an investigation of energy consumption and energy-saving potentials in Miami Exports (PVT) Ltd, Sri Lanka using simulation software. The site has a poor power factor of around 70% with a maximum demand of 452 KVA. With two years of data collection and analysis, the 553 kW solar PV system with a voltage source controller is used to provide the reactive power requirement in the daytime, and a 40 kvar capacitor bank is used to achieve the night-time power factor improvement. The combination of a solar PV system and a capacitor bank is more suitable for integrating into a system in which the demand fluctuation is considerably lower during working hours to minimize the overcorrection of the power factor. It can improve the power factor to 95%. This study demonstrates the efficiency of the power factor enhancement performance for a real-world industrial load, resulting in a cost savings of 905806 LKR from monthly demand fluctuations and a six-year payback period.

REFERENCES

[1] H. Umran, "Study and analysis for the effects of power factor correction in al-najaf cement plant," vol. 8, pp. 59–72, 01 2015.

[2] D. Pubudunee and S. Ediriweera, "An investigation on improvement of power factor: a case study," in *International Conference on Innovation and Emerging Technologies*, 11 2021.

[3] D. Pubudunee and S. Ediriweera, "A case study on improvement of power factor of an industrial load," in *2021 3rd International Symposium on Material and Electrical Engineering Conference (ISMEE)*, 2021, pp. 32–36.

[4] F. Zheng and W. Zhang, "Long term effect of power factor correction on the industrial load: A case study," in *2017 Australasian Universities Power Engineering Conference (AUPEC)*, 2017, pp. 1–5.

[5] R. S. Biswas and S. Mal, "Automatic power factor improvement using microcontroller," in *2015 International Conference and Workshop on Computing and Communication (IEMCON)*, 2015, pp. 1–6.

[6] R. K. Garg, S. Ray, and N. Gupta, "Reactive power compensation and power factor improvement using fast active switching technique," in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016, pp. 1–5.

[7] Zaidi, Maryam Nabihah and Ali, Adlan, "Power factor improvement using automatic power factor compensation (apfc) device for medical industries in malaysia," *MATEC Web of Conferences*, vol. 150, p. 01004, 2018. [Online]. Available: https://doi.org/10.1051/matecconf/201815001004

[8] P. Adoniadis, N. Vordos, D. Bandekas, and A. Ioannou, "Improvement of power factor. technoeconomical application in a case study at the industrial area of kavala," *Electronics and Electrical Engineering*, vol. 118, pp. 1392–1215, 05 2012.

[9] R. El-Mahayni, R. Van De Vijver, R. Rashidi, and A. Al-Nujaimi, "Corporate wide power factor correction application: economic and technical assessment," in *2017 Petroleum and Chemical Industry Conference Europe (PCIC Europe)*, 2017, pp. 1–13.

[10] A. A. Mon and S. W. Naing, "Power factor improvement for industrial load by using shunt capacitor bank," *Int. J. Sci. Eng. Technol. Res*., vol. 3, no. 15, pp. 3191–3195, 2014.

[11] S. Bhattacharyya, H. Choudhury, and Jariwala, "Case study on power factor improvement," *International Journal of Engineering Science and Technology*, vol. 3, 12 2011.

[12] K. Subramanian and S. Tandon, "Power factor correction using capacitors and filters," *International Journal of Engineering and Technology*, vol. 7, p. 234, 04 2018.

[13] M. H. Riaz, M. Zeeshan, H. ul Banna, T. Kamal, and S. A. H. Shah, "Demand side management using different energy conservation techniques," in *2017 International Multi-topic Conference (INMIC)*, 2017, pp. 1–4.

[14] A. A. Ghani, V. K. Ramachandaramurthy, and J. Y. Yong, "Design of a master power factor controller for an industrial plant with solar photovoltaic and electric vehicle chargers," *Electrical Engineering*, vol. 104, no. 1, pp. 13–25, 2022.

[15] A. Zahedi, "Solar photovoltaic (pv) energy; latest developments in the building integrated and hybrid pv systems," *Renewable Energy*, vol. 31, pp. 711–718, 04 2006.

[16] "Power factor correction using capacitor bank," Jul 2018. [Online]. Available: https://electricalacademia.com/basic-electrical/power-factorcorrection/

[17] E. K. Mohammedsaeed and K. Jia, "Comparison of some low voltage ride-through strategies," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 152–157.

[18] A. Refaat, A. E. Kalas, A. A. Daoud, and F. M. A. Bendary, "A control methodology of three phase grid connected pv system," 2013.

[19] R. E. Ramesh e and S. Harsha J, "Voltage source converter based hvdc transmission," *IJESIT*, vol. 1, pp. 97–106, 09 2012.

[20] V. Virulkar and M. Aware, "Modeling and control of dstatcom with bess for mitigation of flicker," 01 2009.