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PEAK POWER ELIMINATION IN AN INDUSTRIAL PLANT WITH CYCLIC OPERATION

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Abstract- Industrial plant with cyclic operation such as concrete mixing plants have a very dynamic power consumption profile, in which the peak power demand is typically 2-3 times if average power demand. The owner of the plant however shall pay for the max. Power demand and shall install the supply equipment with ratings of peak power demand. An energy storage system based on EDLCs can deliver the peak power during the peak power demand which lead to reduce the rating (and cost) of the installed power supply devices without outperforming the plant operation.

Keywords: Peak Power, EDLC, SuperCaps, Industrial Plant, Cyclic Operation.

I. INTRODUCTION

Electric instantaneous power consumption of an industrial plant is highly dependent on the production process and product being produced. A steel or aluminum production plant has constant high power consumption, while, for example, concrete mixing plant has a highly variable power, but with repeated cycles. Despite of a short duration of peak power demand, the plant owner shall contract with the local power supplier based on peak power demand and shall install all the supply equipment (Transformer, Cable or gen-set, etc.) to cope with the required peak power. A proper energy storage system can deliver the peak power which lead to reduce the rating (and cost) of the installed power supply devices.

II. INDUSTRIAL PLANTS WITH HIGH PEAK POWER

Figure 1 shows a typical curve of the absorbed power $P(t)$ of a concrete batching plant over the time t. Through the various activities such as material transport belts, pumps, mixing, cleaning or concrete outgoing results in a very uneven load profile which, however, are cyclic repeated to produce concrete for the next batch. In this figure the instantaneous power consumption P of the plant is depicted with solid line, and resulting average power consumption over the period of a cycle is depicted with dashed line. The peak power for a few second amounts to about 130 kW, which is equal to installed power in the plant, where the average power consumption is only 50 kW, which is only 38% of the peak power demand.

The fluctuating overall power of the drive motors means that the required main transformer, cables and other supply equipment must be sized to the peak value. Looking at the curve shown in Figure 1 the transformer and distribution components therefore have a rated power of 130 kW, which is well above the average power of about 50 kW.

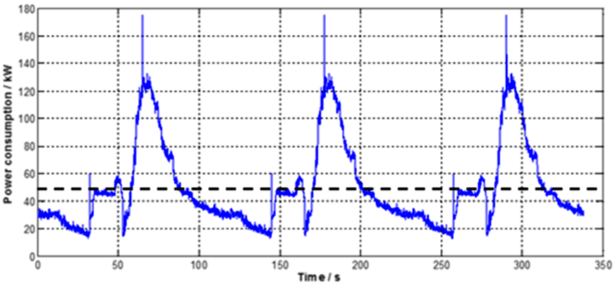

Figure 1. Typical power consumption of a concrete mixing plant with cyclic (Batch) operation

Plant owner shall contract with the local utility company based on the peak power demand of the plant, independent of its duration. Moreover the owner shall carry higher costs for distribution transformer, cables, and other required distribution facilities. In deed the owner pays regularly more money for a demand, which is only consumed within a very short period over a cycle.

This oversizing of the individual components is reflected significantly higher investment costs. Furthermore, some network operators and energy suppliers require extra fees because the network load varies greatly with resulting voltage drops. Moreover, due to result of voltage dips, operation in weak networks could lead to system fault. This is particularly the case for mobile plants on construction sites, since the network connection cannot be often adequately ensured.

Figure 2 depicts a simplified diagram of a conventional electrical power distribution in an industrial plant comprising dynamic loads (motors) and VAR compensation facility as well as active filter. The connection to the high voltage public network is done through a power transformer. The motors are powered by inverters with integrated soft starting function for large motors. The fluctuating overall power of the drive motors means that the required power transformer, cables and the other distribution components must be sized to the peak value. Looking at the diagram shown in Figure 2 the transformer must therefore have a rated power of 130 kW, which is well above the average power of 50 kW.

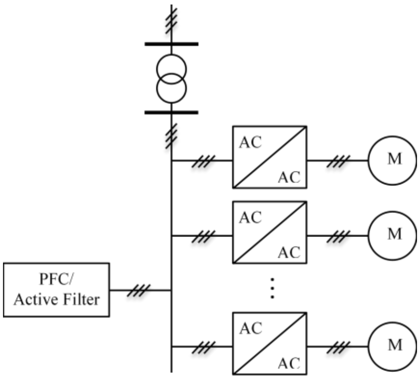

Figure 2. Simplified diagram of the power distribution in an industrial plant comprising dynamic loads (motors) and VAR compensation

In case of a mobile plant which is operated in an area without electric network access, the required power is supplied by diesel/generator set. In this case the gen-set shall be calculated with the peak power too, which leads to a significant investment.

III. ELIMINATION OF PEAK POWER BY USING ENERGY STORAGE

The object of this investigation is to provide a device and method for electric power supply of an industrial plant with periodic power consumption, capable of eliminating the peak power demand and smoothing the demand profile during the cycle operation, without outperforming the total plant operation.

The suggested system is connected between the electric power network and loads, in particular electric motor of concrete mixing plant. In this case, the power supply system can be a public power network as well as gen-set. Alternatively, it may also be an independent local power generator.

The suggested system, which is capable of reducing the peak power, is an energy storage unit combined with a DC/DC converter and an energy management unit. The AC power is first converted in DC power through a rectifier unit, so that all main drives (power consumers) are connected commonly to a main DC-Bus. The energy storage unit is connected according to the Figure 3 through the DC/DC converter parallel with the loads through the main DC-bus to the power supply network or local energy supply system. During the low consumption periods the storage unit can be switched in charging modus. In this modus the network supplies the plant loads and simultaneously charges the storage unit. During the peak periods the storage unit is switched in discharge modus. In this case the storage unit and the network supply together the plant loads. In both cases the network supplies the mean power demand and the storage unit supplies the peak power demand. The capacity of the storage system shall be then calculated based on power consumption curve of the plant in the next section.

Further, a power management system is provided which controls the instantaneous power flow. For this purpose the instantaneous power consumption of the plant and the state of charge (SOC) of the storage unit are measured and fed to the energy management system. Further, the cyclic power profile of the plant as a-priori-information is stored in the energy management system as well and is used for load forecasting. The power management dependent on the instantaneous power demand, SOC of storage system and the load forecasting-provides electrical energy in three modes of operation:

- Feeding from Network or primary source (e.g. gen-set)
- Feeding from storage
- Feeding from network and storage commonly

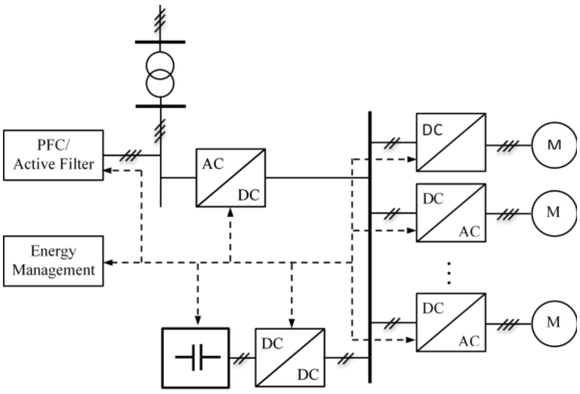

Figure 3. Simplified diagram of the power distribution in an industrial plant equipped with energy storage and energy management unit

As electrical energy storage unit two main devices could be considered. The first category is battery. The typical batteries which could be used are dry Lead batteries and Li-ion batteries. The second category is electrochemical double layer capacitors EDLC.

Generally the batteries have a large energy density and lower power density. On the contrary the EDLCs have lower energy density and higher power density. These properties of storage systems are normally demonstrated in the so called Ragone chart.

A Ragone chart is a chart used for performance comparison of various energy-storing devices [1]. On such a chart the values of energy density (in Wh/kg) are plotted versus power density (in W/kg). Conceptually, the vertical axis describes how much energy is available, while the horizontal axis shows how quickly that energy can be delivered, otherwise known as power, per unit mass. A typical Ragone chart is demonstrated in Figure 4.

IV. ELECTRIC DOUBLE LAYER CAPACITORS AS STORAGE DEVICE

Electric double-layer capacitors (EDLC) -often called supercapacitors- are storage devices that have a structure similar to electrolyte capacitors, with two electrodes, electrolyte and a separator. The capacity of the EDLCs can be varied from 1 F to several thousand Farads with a cell voltage of 2.7-2.8 V. Therefore, several cells are usually connected in series to provide a capacitor bank with higher voltages.

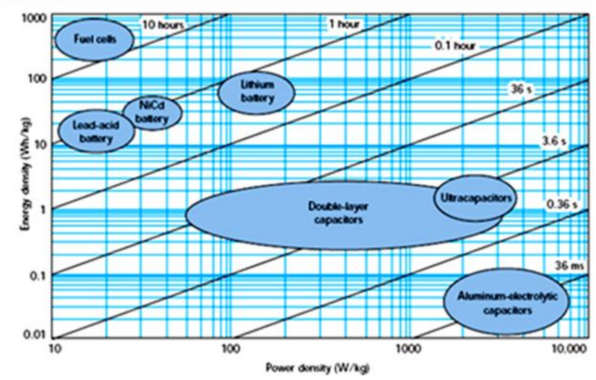

Figure 4. Ragone chart for different types of energy storage devices

In opposite to batteries in which a chemical reaction generates electrical energy, here the energy is stored solely in the electric field at the phase boundary between electrolyte and electrode, the so called electrostatic double layer [2].

Several phenomena contribute to the double layer capacitance, the two predominant effects which are used to explain the separation of charges are the compact and the diffuse layer. The compact layer was first described by Helmholtz. The basic idea of the Helmholtz model is a compact layer of ions at the surface of the electrode, the thickness of the Helmholtz layer is thus determined by the effective ion radius. A second contribution to the double layer is the diffuse layer described by the Guoy-Chapman model that takes the thermal fluctuation of charge carriers into account [2].

Electrostatic double-layer capacitors use electrodes coated with active carbon or derivatives with very high electrode surface area about 1000 m²/g which results in a specific capacitance of 100 F/g. Higher surface areas are achieved by using CNT, graphene and other derivatives up to 2500 m²/g corresponding to 350 F/g [3, 4].

Electrostatic double-layer capacitors offer high power density and extremely high cycling capability. Recent technology improvements enabled EDLCs to be an interesting option for short-term high-power applications, such as in industry, automotive and traction drives, regenerative energy systems and medical and telecommunication equipment [5, 6].

They typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries. They are however 10 times larger than conventional batteries for a given stored energy.

V. SIZING OF THE ENERGY STORAGE

It should be mentioned, that the design procedure is an iterative one, because it should be tailored to the ratings of available components and some other requirements like cost and volume optimization of the capacitor bank and DC/DC-converter. The first step in the sizing an EDLC based storage system is to determine the required energy in one operation cycle of plant which shall be covered by storage. As mentioned above the arithmetic average of the power consumption of the plant under test in one operating cycle is about 50 kW, where the peak power during the peak load amounts to 130 kW. In Figure 5 the peak power period is depicted with a triangle. The area of this triangle is approximately equal the required energy during the peak power interval. The calculation of the total energy demand in on production cycle as well as peak energy demand is done by integrating the power data acquired by digital data acquisition device in desired time intervals.

The total energy demand in on production cycle which takes 110 s is:

$$E_{cycle} = \int_{T_0}^{T_{end}} P(t)\,dt = \int_{0}^{110} P(t)\,dt \approx 5466 \text{ kJ} \tag{1}$$

For calculation of peak power demand we find the intersections of the power curve with average consumption, i.e. T_1=56 s and T_2=85 s.

$$E_{peak} = \int_{T1}^{T2} P(t)\,dt = \int_{56}^{85} P(t)\,dt \approx 1230 \text{ kJ} \tag{2}$$

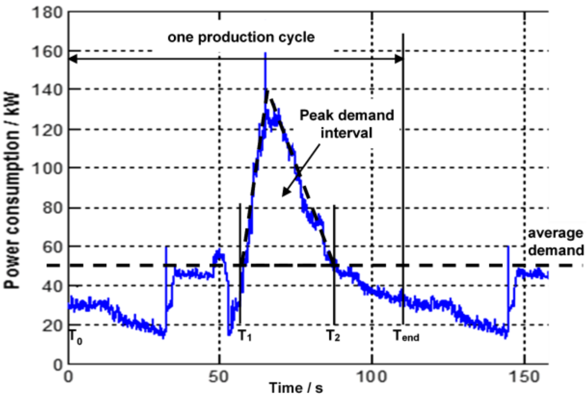

Figure 5. Power demand profile of the plant in one production cycle, average power is depicted with dashed line, the peak power demand is surrounded within a triangle

According to the system configuration of Figure 3 the base power demand 50 kW shall be supplied by power grid (or gen-set), where the required energy in the peak demand interval shall be stored in the capacitor bank during the low consumption interval and will be delivered during the peak demand interval to the plant.

The stored energy in a capacitor bank with a total capacitance of C and total voltage V is given

$$E_C = \frac{1}{2} C V^2 \tag{3}$$

The Stored energy in the storage device E_C shall be higher than the required energy in the peak demand interval. Since the storage device is connected to the entire system according to Figure 3 through a DC/DC converter, we choose a proper relation between the voltages of the low and high sides to keep the volume of the inductive elements in the DC/DC converter reasonable. In this case a ratio of $V_{low} / V_{high} = V_{Storage} / V_{DC\text{-}bus} \approx 0.5$ is chosen, so that the voltage of the capacitor bank at T_2 i.e. (end of discharge interval) can be converted to the nominal DC-bus voltage with a factor of two. Under this condition the remaining charge in the capacitor bank at the end of interval is equal to:

$$E_C\,|_{T1} = \frac{1}{2}CV_{T1}^2 = \frac{1}{2}CV_{DC-bus}^2 \quad (4)$$

$$E_C\,|_{T2} = \frac{1}{2}CV_{T2}^2 = \frac{1}{2}C(\frac{1}{2}V_{T1})^2 = \frac{1}{2}C(\frac{1}{2}V_{DC-bus})^2$$

$$E_C\,|_{T2} = \frac{1}{4}\times\frac{1}{2}CV_{DC-bus}^2 = 0.25E_C\,|_{T1} \quad (5)$$

In other words, the voltage of the capacitor bank at the end of peak demand interval is reduced to 50% if the 75% of the stored energy is discharged during this interval. So we can calculate the total stored energy in the capacitor bank:

$$\begin{aligned} &E_{peak} = 0.75E_c\,|_{T1} \\ &E_C\,|_{T1} = 1640 \text{ kJ} \end{aligned} \quad (6)$$

The nominal voltage of the DC-bus is designed to 560 V, however it varies between 480 V to 620 V. Considering the lower limit of the DC-bus voltage 480 V as $V|_{T1}$ (fully charged capacitor bank) and the required energy stored in the capacitor bank as $E_C\,|_{T1}$, the total capacitance of the storage device is

$$C = \frac{2E_C\,|_{T1}}{V_{DC-bus}^2} = \frac{2.1640\times10^3}{480^2} = 14.24 \text{ F} \quad (7)$$

Normally with the sizing of an EDLC capacitor bank the end of life capacitance and internal resistance of the EDLC cells shall be considered. When referring to EDLC life the data sheets reflect the change in performance, typically decrease in capacitance and increase in internal resistance. The EDLC does not experience a true end of life rather the performance continually degrades over the life of the use of the product. The typical lifetime of the EDLC cells is defined as a time, at which the cells capacitance is reduced to 80% and the equivalent series resistance (ESR) increase to 200% referred to their nominal values. Thus the required capacitance of the capacitor bank considering the lifetime is

$$C_{new} = \frac{C}{0.8} = 17.8 \text{ F} \quad (8)$$

To complete the design procedure we calculate the required number of cells, which are connected in series in the capacitor bank. The nominal voltage of the capacitor bank was chosen as 480 V. Considering the nominal cell voltage of 2.7 V, the required number of cells is thus

$$n = \frac{480}{2.7} = 177.78 \text{ cells} \quad (9)$$

We choose totally 180 cells to build the capacitor bank. This 180 cells are grouped in 6 separate modules each containing 30 cells.

The next step is the calculation and choose of cells. To calculate the capacitance of the cells we used the well-known formula

$$C_{cell} = nC_{new} = 180\times17.8 = 3204 \text{ F} \quad (10)$$

The nearest capacitance of the commercially available cells are 3000 F and 3400 F. The cells with a capacitance of 3400 F are chosen, so we achieve a better design margin. Figure 6 shows the developed module containing 30 cells, each 3400 F and 2.7 V. The capacitance and the nominal voltage of the module is then 113 F and 80 V respectively. Totally 6 modules are built and connected in series to have a capacitor bank of 18.89 F (15.11 F end of life capacitance) and 480 V.

Entirely the capability of the capacitor bank to deliver the maximum required power $P_{\max}$ in the peak demand interval shall be examined. According the manufacturer data sheet, the maximum power, which an EDLC capacitor bank can deliver is

$$P_{max} = \frac{V^2}{4ESR} \quad (11)$$

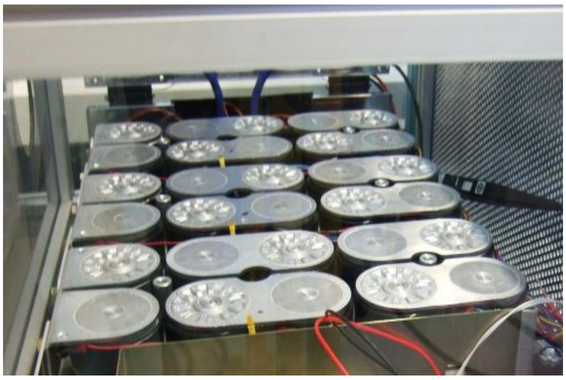

Figure 6. EDLC storage module with 30 cells under test

The total *ESR* is the series connection of *ESR* of 180 single cells. The *ESR* of a single cell according the data sheet [7] is 0.28 mΩ. Similar to sizing of cell capacitance with calculation of total *ESR* the cell lifetime shall be considered. As mentioned above, the *ESR* at the end of lifetime increases 100%. Thus the total *ESR* of the capacitor bank considering the lifetime is

$$ESR_{bank} = 180\times2\times ESR_{cell} = 100.8 \text{ m}\Omega \quad (12)$$

Considering additional 180 mΩ for the internal connection of the cells and about 20 mΩ for the cables and connectors the total internal resistance of the capacitor bank amounts to 300 mΩ. Substituting this value in Equation (11) the maximum power delivery of the bank is then

$$P_{\max} = \frac{V^2}{4ESR} = \frac{480^2}{4\times300} = 192 \text{ kW} \quad (13)$$

which is much higher than the maximum power consumption $P_{\max}$ = 80 kW during the peak demand interval T_1-T_2. The capacitor bank shall supply through the DC/DC converter this power during the peak demand interval with a voltage of 240 V (half of the nominal voltage) as the worst case. This means that

$$I_{bank} = \frac{P_{\max}}{0.5V_{bank}} = \frac{80000}{0.5\times480} = 312.5 \text{ A} \quad (14)$$

According to the manufacturer data sheet [7] the maximal permissible cell current is 2000 A which is much higher than the calculated value.

VI. RESULTS OF INSTALLING THE ENERGY STORAGE IN PLANT

The developed EDLC storage and a DC/DC converter with interleaved topology as well as energy management controller were installed in the plant under study. The total energy consumption of the plant remains constant, however the energy demand during the peak power interval is divided in two components, the first component is supplied by power network and the second one is delivered by Capacitor bank.

Figure 7 depicts the power curves measured at the terminals of the storage system P_C and at the mains connection point P_N. The total energy consumption of the plant has not been changed, however the contracted power and the ratings of power supply equipment are reduced to 50 kW. The maximum power delivered by capacitor bank during the peak demand interval is about 80 kW, which coincides to the calculated value.

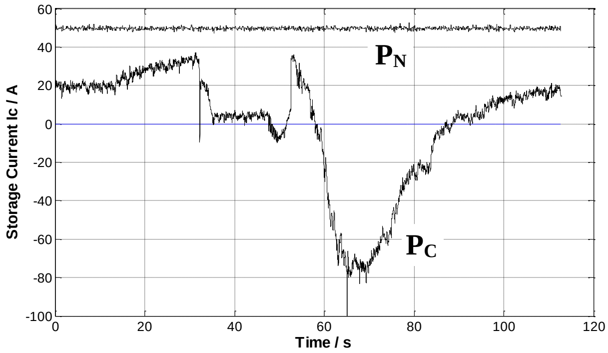

Figure 7. Network Power P_N and Capacitor Bank power P_C. Positive values of P_C mean charging and negative values mean discharging of storage system

Figure 8 depicts the current profile of the capacitor bank. The maximum current occurs during the peak demand interval and accounts to 200 A, which is smaller than the calculated worst case (Equation (14)).

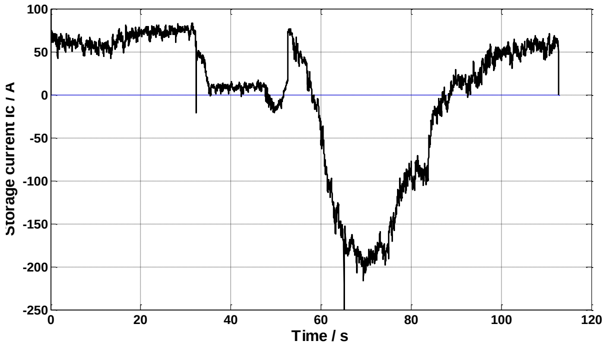

Figure 8. Capacitor Bank Current I_C. Positive values of I_C mean charging and negative values mean discharging of storage system

In Figure 9 is shown the capacitor bank voltage. As calculated the voltage of the capacitor bank is reached its maximum value 480 V at the beginning of the peak demand interval T_1=56 s. After discharging the stored energy reaches the storage voltage at T_2=84 the half voltage value of 240 V.

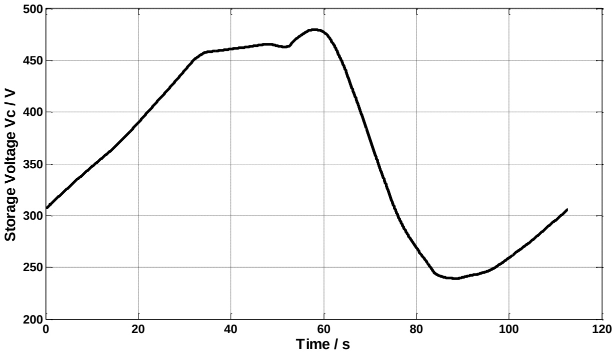

Figure 9. Capacitor bank voltage V_C. The capacitor bank voltage swings between $V_{\max}$ = 480 and $V_{\min}$ = 240 V

VII. CONCLUSIONS

Using EDLC based capacitor bank as storage systems in an industrial plant with a cyclic operation and a large peak power demand led to smoothing the power demand profile and reduce it to a constant power demand. This led to a reduced contract fees with local power supplier and a reduced investment for power supply equipment (transformer, switchgear, cables, etc.). This saving can easily compensate the investment for storage system, DC/DC converter and energy management. Using such system is especially in locations with weak power network is advantageously and increase the flexibility of plant installation and operation.

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BIOGRAPHY

Nejat Mahdavi Tabatabaei was born in Tehran, Iran, 1964. He received his B.Sc. degree in Electrical Power Engineering from University of Tabriz, Tabriz, Iran, M.Sc. (Dipl.-Ing.) and Ph.D. (Dr.-Ing.) degrees in Control and Instrumentation from University of Kassel, Kassel, Germany. In 1998-2002, he joined to University of Tabriz as lecturer and 2002-2007 was as scientific staff at University of Kassel. Since 2007 he is a senior research engineer in Liebherr-Elektronik in Germany. Since 2010 he is a lecturer at Baden-Wuerttemberg Cooperative State University (DHBW) in Friedrichshafen, Germany. Since 2013 he is an Assistant Professor at Seraj higher Education Institute, Tabriz, Iran. His research areas are control engineering, sensors, hybrid vehicles and energy storage systems.