MODELING AND DESIGN OF A RELIABLE LOW VOLTAGE POWER DISTRIBUTION SYSTEM

ARVIND RAJIV
CKR Consulting Engineers, Dubai, U.A.E
E-mail: arvind@ckr.ae

Abstract— Electrical Engineers today are facing numerous problems related to design of safe and reliable electrical power distribution systems. In order to design a reliable power distribution system, it is imperative that the engineer takes into consideration all the factors that pertain to the safety aspects of the power distribution system. Ideally, a reliable power distribution system is one that is least prone to electrical hazards, and delivers electrical power at its highest quality and minimal losses. This paper deals with the design and modelling of a power management system that distributes electrical power with maximum power quality and safety and minimal losses during distribution.

Index Terms— Power Management System, Power Distribution, Power Quality, Reliability.

I. INTRODUCTION

The primary function of an electric power distribution system in a building, is to receive power from the substation, and distribute it to each and every load within the building that is operated electrically. Examples of such loads are motor loads for wet services, motor loads for heating, ventilation and air condition (HVAC) and lighting loads. In order for the distribution system to safely deliver power, the occurrence of faults should be minimal. If the system is not equipped with efficient fault protection devices, the occurrence of faults is most probable, and its effect on the building could be catastrophic.

To mitigate the issues of fault occurrence on power distribution systems, protection devices such as circuit breakers, fuses and relays should be used at all stages of the power distribution. Statistical data from the National Fire Protection Association depicts the percentage of home fires involving electrical distribution and lighting equipment from 2007 to 2011 as below in Fig. 1. [1].

![Figure 1: Statistical Data of Home Fires due to Electrical Distribution from 2007-2011](image)

From Fig. 1, it can be inferred that if an electrical hazard arises in a building, its cause is most likely due to improper wiring of cables and conduits that are connected to the electrically operated loads within the building and also ignorance of safety during the design stage of the power system. The statistical data also reveals that these electrical hazards can cause civilian deaths. Thus, it becomes imperative to design electrical distribution systems that produce least electrical hazards, to ensure the safety of not only the electrically operated loads, but also the civilians within the building.

The factors that define a safe power distribution system are umpteen. The key factors that require consideration during the design stage of the power distribution system are as below.

- Characteristics of the load the distribution system has to feed.
- Rating of capacitor banks to achieve the desired power factor.
- Voltage drop from the point of supply to final sub-circuit.
- Routing of the containment till the electrical load.
- Spacing between the cables that are placed in the containment.

By taking into consideration the above points, one can ensure that the distribution system provides electrical power with high power quality along with maximum safety to ensure that no electrical hazards arise.

In order to clearly understand how an efficient power distribution system is designed, the paper will first deal with how the power system is to be modelled with the given loads within the building considered, and then a detailed study of the external factors that affect the distribution of power to these loads will be done in order to design the protection scheme for the distribution system and the final Single Line Diagram for the power distribution system.
II. MODELING OF THE POWER SYSTEM

In this paper, a 10 storey residential tower with apartments in each floor was considered. The aim of the power system is to distribute electrical power from the Substation Transformer up to the final socket points within the entire building. In order to ensure safe distribution of power from the substation transformer, the power system was modeled such that power gets transmitted in branches in order to reach the end user. It is necessary to provide circuit breakers at every stage of power transmission in order to ensure that the power system is safe to rely on for power distribution. The most important factor that needs to be considered before modeling the power system is the calculation of voltage drop from the main distribution board till the final sub circuit. Fig.2., which was drawn using ‘AutoCAD Electrical’ denotes the flow of power from a 1500KVA Dry Type Cast Resin Substation Transformer to the Main Distribution Board, followed by the flow of power from Main Distribution Board to the Sub Main Distribution Board, followed by flow of power from Sub Main Distribution Board to Final Distribution Board, and finally from the Final Distribution Board up to the final sub circuits which include sockets.

The main distribution board is the panel through which the electrical energy from the substation, which is used to feed the final sub circuits is taken from the substation. It typically houses the main circuit breakers, ground leakage protection, metering equipment and the supporting current transformers in stages. The electrical power from the MDB (Main Distribution Board) is then supplied to the Sub Main Distribution Board (SMDB) through high rating cables. The Sub Main Distribution Board is the panel through which electrical power from the MDB is fed to the Final Distribution Board. It houses protection devices such as High Rupturing Capacity Fuses (HRC) fuses, Miniature Circuit Breakers (MCB’s) or Molded Case Circuit Breakers (MCCB’s). Power from the Final Distribution Board is then fed to the final sub circuits through wires. Once the power flow stage was prepared, detailed calculation of certain parameters was done for each panel of the distribution system in order to ensure maximum safety of power distribution. The factors to be calculated for each Panel are as below:-

1. Total Connected Load
2. Rating of the circuit breaker
3. Voltage Drop
4. Size of Incoming Cables

The detailed calculation of each panel of the single line diagram from upstream to downstream was done and is discussed in detail as below.

III. CALCULATIONS FOR MAIN DISTRIBUTION BOARDS

(i) Total Connected Load (TCL):
The total connected load of the main distribution board was calculated by estimating the total power requirement of all the loads it is feeding.

(ii) Sizing of the Circuit breaker for the Main Distribution Board
Ideally, the circuit breaker protecting the Main Distribution Board, is required to have high current carrying capacity of up to 63kA. Due to this reason, an air circuit breaker rated up to 2500A was used to protect the Main Distribution Board.

IV. CALCULATIONS FOR SUB MAIN DISTRIBUTION BOARDS

(i) Total Connected Load (TCL):
The total connected load of each sub main distribution board was calculated by estimating the total power requirement of all the continuous operating (operating 3 hours or longer) and non-continuous loads it was feeding.

(ii) Sizing of the Circuit breaker for the Sub Main Distribution Board
Ideally, circuit breakers shall be designed to withstand 125% rated current of the continuous loads and 100% rated current of the non-continuous loads. Consider the breaker sizing calculation below:

Continuous operating load of the SMDB in Amperes = 50A
Acceptable Rating of Circuit Breaker = 125% Continuous + 100% Non-Continuous Load
Thus, Acceptable Rating of Circuit Breaker = 187.5A
V. PERCENTAGE OF VOLTAGE DROP CALCULATION

Calculation of percentage of voltage drop from the substation transformer up to the final sub circuits in a building is of utmost importance as excessive voltage drop may result in unsatisfactory operation of, and damage to, electrical and electronic equipment. The percentage of voltage drop from substation transformer till the final sub circuit varies for different countries as the standards of electrical installation differ for different countries.

According to the regulations of Dubai Electricity and Water Authority, the maximum permissible voltage drop from the substation transformer up to the final sub circuit should not exceed 4% of the nominal voltage of the electric supply [2]. It is mandatory to consider this limit while performing the voltage drop calculations.

The voltage drop calculations were calculated in steps as mentioned below:-

(a). Main Distribution Board to Sub Main Distribution Board (via busbars or cables mounted on cable trays).

(b). Sub Main Distribution Board to Final Distribution Board.

(c). Final Distribution Board to sub circuits.

The voltage drop of a busbar was obtained by implementing the equation given below:

\[ V_d = \sqrt{3} \times I^2 \left( R_L \cos \Phi + X_L \sin \Phi \right) \]  

Where \( V_d \) is the voltage drop, \( I \) is the rated current of the Main Distribution Board that the copper busbar is connected to, \( R_L \) is the resistance offered by the copper busbar, and \( X_L \) is the reactance offered by the copper busbar.

The rated current of the Main Distribution Board was obtained by using the equation below:

\[ I = \frac{TCL}{\sqrt{3} \times V \cos \Phi} \]  

Where TCL is the total connected load of the Main Distribution Board, \( V \) is the System Voltage, and \( \cos \Phi \) is the power factor.

Since the MDB was to feed SMDB’s located in upper floors of the building, it was preferred to use vertical busbars rather than cables as the cumulative voltage drop from the MBD till the final distribution point reduced when a busbar was being implemented. As the vertical busbar rises in each floor, electrical power was distributed from the busbar to each SMDB via. Tap-off units, which is an outgoing unit for tapping off power from a busbar trunking system. Vertical busbars feeding SMDB’s at higher floors are classified into two types [3]:

1. Feeder Busbar: The part of the busbar where the first tap-off is implemented.
2. Distributed Load Busbar: The part of the busbar where the load is tapped off the busbar along its length.

The busbar implemented in this model is a 3200A TPN (Three Phase Neutral) copper busbar. The technical details of the busbar, such as the cross sectional area, resistance, reactance and impedance of the TPN Busbars as shown below in Fig.3 below.

![Fig.3. Technical Data Sheet of the 3200A TPN Copper Busbar](image)

When the voltage drop of the busbar was to be calculated, the total voltage drop of the entire length of the busbar was cumulative sum of the voltage drop at the feeder busbar and distributed load busbar. As a rule of thumb, the full load voltage drop of the distributed busbar may be divided by 2 to give the approximate voltage drop at the end of the distributed load busbar [4].

The voltage drop calculation of the busbar in this used in this model is as shown in Table 1 below:-

<table>
<thead>
<tr>
<th>Voltage Drop Calculation of Busbar feeding 6th Floor Sub Main Distribution Board</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD (kVA)</td>
</tr>
<tr>
<td>REACTIVE POWER (kVAR)</td>
</tr>
<tr>
<td>VOLTAGE DROP (kV)</td>
</tr>
<tr>
<td>TOTAL VOLTAGE DROP (%)</td>
</tr>
</tbody>
</table>

After the voltage drop of the busbar was calculated, the drop at the SMDB’s that are being fed directly from the MDB through cables were to be calculated. The factors that affect the voltage drop of cables are as below:-

1. Total Connected Load (TCL) of the panel the cable is feeding.
2. Power Factor
3. Load Current
4. Length of the cable feeding the SMDB from the busbar tap-off unit

By knowing the total connected load of the panel and the power factor, the load current of the three phase panel was calculated using the formula below:

\[ I = \frac{V_{CL}}{\sqrt{3}V \cdot \cos \theta} \]  

(3)

Where \( V \) is the standard system voltage (400V in United Arab Emirates).

After obtaining the load current through the cable, the voltage drop of the cable feeding the SMDB was calculated by using the equation below:

\[ V_{d} = \frac{V_{m} + II \cdot L}{1000} \]  

(4)

Where \( V_{m} \) is the voltage drop caused by the natural properties of the cable, which can be obtained from the technical data sheet of the cable being implemented to feel the concerned load.

By obtaining \( V_{d} \) the percentage of voltage drop produced by the cable can be obtained from the equation below:

\[ V_{drop} = \left( \frac{V_{d}}{V} \right) \times 100 \]  

(5)

By obtaining the percentage of voltage drop from the busbar tap-off to the SMDB, the percentage of voltage drop from the SMDB to the final Distribution board was obtained by using equations 3, 4 and 5.

After calculating the step by step percentage of voltage drop from the Main Distribution till the Final Distribution board by using the above points, the total percentage of voltage drop was calculated by obtaining the cumulative sum of percentage of voltage drop of all the stages of power distribution. The percentage of voltage drop from the Main Distribution Board to each Final Distribution Board is as shown below in Table 2.

### VI. REACTIVE POWER MANAGEMENT THROUGH POWER FACTOR CORRECTION

Since the loads that the transformer was feeding in the AC electrical network were predominantly inductive, it would result in the circulation of reactive power in the electrical network [5]. This circulation of reactive power in the electrical network leads to major consequences which are mentioned below [6]:-

(i) Overload of the transformer feeding the main distribution board
(ii) Large Voltage Drop
(iii) Higher energy consumption and hence higher temperature rise of supply cables.

Due to the above reasons, it is imperative to manage reactive power flow by generating reactive power at the end consumer level, rather than generating reactive power at the power generation level. This act is called reactive power compensation and can be achieved by implementing capacitor banks. In order to define the rating of the capacitor bank (in KVAR), the total connected load of the Main Distribution Board and the corresponding power factor needs to be known. The calculation of the rating of the capacitor bank for this model is explained in detail in the section below:

A. Segregation of loads fed by the transformer

In order to size the capacitor bank, the connected load of each load the SMDB is feeding is to be determined. A detailed segregation of the connected load for each type of load, in each floor of the building was obtained and is as shown in the table below.

After modeling the induction motor, analysis was done by simulating the motor under different conditions. The software, which considers the real-time parameters of the machine, performs finite element analysis for every 1.75ms over a span of 325ms. By analyzing the machine, the machine parameters like magnetic flux, voltage and current distribution have been obtained. The model of the analyzed three phase squirrel cage induction motor is as shown in Fig.4.
It was observed that with the given loads in the building, the overall power factor was 0.8. However, this power factor is generally poor and hence needs to be improved to a value of at least 0.92. In order to achieve this power factor, automatic reactive power compensation needs to be implemented. This can be achieved by calculating the Total Connected Load of all the Inductive Loads that are being fed by the Main Distribution Board. The calculation of total connected load of all inductive loads is as shown in Fig.5.

<table>
<thead>
<tr>
<th>LOAD TYPE</th>
<th>TCL IN kW</th>
<th>POWER FACTOR</th>
<th>TCL (INDUCTIVE) Kw</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMALL POWER</td>
<td>363.00</td>
<td>0.80</td>
<td>363.00</td>
</tr>
<tr>
<td>BLOWER</td>
<td>8.19</td>
<td>0.00</td>
<td>8.19</td>
</tr>
<tr>
<td>DRYER</td>
<td>56.00</td>
<td>0.00</td>
<td>56.00</td>
</tr>
<tr>
<td>WASHER</td>
<td>56.00</td>
<td>0.00</td>
<td>56.00</td>
</tr>
<tr>
<td>FCU</td>
<td>26.36</td>
<td>0.80</td>
<td>26.36</td>
</tr>
<tr>
<td>ALCOHOLATOR</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>772.16</strong></td>
<td><strong>0.80</strong></td>
<td><strong>772.16</strong></td>
</tr>
</tbody>
</table>

On completion of the above calculation, it was observed that the cumulative sum of all the inductive loads that are fed by the Main Distribution Board was 772.16kW. With the total connected inductive load, overall power factor and required power factor, the rating of the capacitor bank was calculated. The calculation of the capacitor bank rating is as shown below:

- Initial Power Factor (\(\cos \Phi_1\)) = 0.8
- Required Power Factor (\(\cos \Phi_2\)) = 0.92
- Total Connected Load of all Inductive Loads (\(P\)) = 772.16kW
- \(\tan(\cos^{-1}(\Phi_1)) - \tan(\cos^{-1}(\Phi_2)) = 0.32\)
- \(P^*(\tan(\cos^{-1}(\Phi_1)) - \tan(\cos^{-1}(\Phi_2))) = 254.81 \text{ KVAR}\)

Thus, from the above calculations, it was observed that in order to improve the overall power factor of the main distribution board from 0.8 to 0.92, a 254.81 KVAR capacitor bank is required to be connected to the main distribution board. However, as most of the suppliers of capacitor banks do not offer a 254 KVAR capacitor, the next available rating of capacitor bank (300KVAR) was chosen in this model.

**VII. OBSERVATION AND RESULTS**

By performing the voltage drop calculations of busbar and cables, the cumulative voltage drop in percentage from the MDB till the final circuits was calculated in order to size the busbar and cables correctly. In addition to the voltage drop calculations, the calculation of sizing the capacitor bank was conducted in order to ensure proper correction of overall power factor. With the results of the calculations, the overall flow of power from the MDB till final sub circuits were correctly designed and the Final Single Line Diagram that denotes the flow of power from the utility transformer till final sub circuits was designed. The Single Line Diagram of the designed model which was developed using ‘AutoCAD Electrical’ is as shown below in Fig.6.

**CONCLUSION**

The Low Voltage Power Distribution System was successfully designed by sizing the circuit breakers for each panel based on their total connected load. The calculation of percentage of voltage Drop of the busbar and cables feeding each Sub Main Distribution Board and Final Distribution Board was performed. It was also ensured that the cumulative percentage of voltage drop from the Main Distribution Board up to the final sub circuits in the building does not exceed 4% of the nominal voltage of the electric supply, to make sure that the design was in compliance to the regulations of the Electricity Authority. The calculation of rating of the capacitor bank was also conducted to ensure that the capacitor bank was suitably sized to ensure that reactive power compensation was efficiently performed. From the calculations and final design, it was inferred that the power system was capable of distributing electrical power from the Substation Transformer up to the final sub circuits efficiently with maximum safety and minimal losses during distribution.

**REFERENCES**


★★★