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Analysis of Electrical Model of Data Center Power System

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Abstract. The electrical structure of the power distribution system in data center is generally a tree-like structure, with fewer branches closer to the power supply side and more branches closer to the load side. In this article, the electrical topology structure diagram is established, and the structure of power distribution network between 10kV input line and power distribution units is discussed. In the electrical structure of power system, 10kV distribution cabinets and 400V distribution cabinets are connected with electrical equipment such as electrical cable, transformer or enclosed busbar. By analysing the equivalent impedance model of equipment above, the theoretical impedance values are obtained.

1. Introduction

Data center power system usually refers to the system used for power transmission and distribution inside the data center, including power distribution cabinets which contain breakers, transformers, electrical cables, enclosed busbars and other equipment. As one of the important systems of the data center, it provides electrical power to the IT system, cooling system and monitoring system in the data center. The reliable and stable operation of the power distribution system provides a powerful power guarantee for the data center. Once it crashes, the normal business of the data center would be seriously affected.

Nowadays, the maintenance of the power system is mainly relying on manual patrol inspections to find weaknesses and accidents in the power system. After the application of the data center infrastructure management system(DCIM), real-time monitoring of highly intelligent equipment such as uninterruptible power supplies and power distribution units can be achieved, pushing equipment status and alarming of crashes and accidents. But for those equipment such as the electrical cables and enclosed busbars used to connect electrical equipment cannot be remotely monitored in real time. Therefore, it is hard to detect hidden dangers of the electrical cables and enclosed busbars early. Usually, emergency measures could be taken after appearance of power system crash caused by short circuits or open circuits.

In this article, according to the real data center power system, the schematic of power system is shown. Then impedance model of electrical equipment such as cable, enclosed busbar and transformer is discussed. The electrical model of power system could be established with the specification of equipment used in real power system.

2. Electrical structure of power system in data center



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According to GB50174-2017 “Code for design of data centers” [1], the data centers could be divided into three levels: tier A, B, or C. The power failure in tier A data center may lead to data loss or network interruption, causing huge economic or social loss. According to the service level agreement(SLA), the power system should maintain high availability, guaranteeing that IT servers are powered without failure.

In a conventional tier A data center, two independent power supply are automatically or manually switched when one of them stopped. Considering that under normal operating conditions, the power system can be regarded as two single-line mains systems that operate independently. Therefore, this article researches the power system with only one power supply.

According to the real distribution of loads, the schematic of power system in data center is shown in figure 1. Because of long distance between transformers and 10 kV busbars, impedance of electrical cables or enclosed busbars could not be ignored. When the transformer is operating normally, there are also some short-circuit losses and excitation losses. Therefore, this article intends to establish an impedance model with the cable, enclosed busbar and transformer.

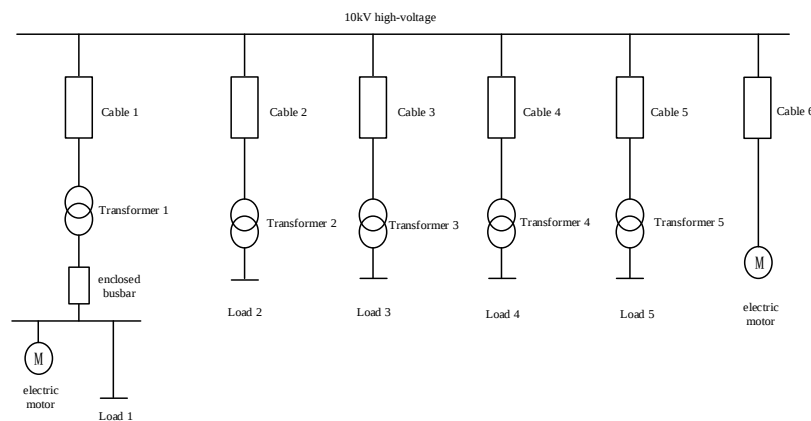


Figure 1 Schematic of Power System

3. Impedance model of electrical equipment

3.1. Impedance model of cable

Electrical cables can be classified according to the diameter, the number of wires, and the insulation material. The cables used for 10 kV voltage are mostly cross linked polyethylene insulated electrical cables(referred to as XLPE cables), while polyvinyl chloride insulated power cables(referred to as PVC cables)are mostly used for 400V voltage cables. The following are calculations and comparative analysis of the two cables' parameters such as capacitance, inductance, and impedance.

3.1.1. Capacitance calculation

The capacitance value of single-core PVC cable is

$$C = \frac{0.445}{\ln \frac{r_i}{r_c}} \quad (1)$$

Single-core XLPE cable capacitance value is

$$C = \frac{0.139}{\ln \frac{r_i}{r_c}} \quad (2)$$

In the formula: r_i is the insulation radius (mm), and r_c is the wire radius (mm).

When talking about three-core cable, the capacitance value of PVC cable is

$$C = \frac{1.335}{G_x} \quad (3)$$

XLPE cable capacitance value is

$$C = \frac{0.417}{G_x} \quad (4)$$

In the formula: G_x is the geometric factor according to the Book of Wire and Cable[2].

The calculated capacitance of PVC cables and XLPE cables with 50 mm²、120 mm²、240 mm² single conductor cross-sectional area are shown in table 1.

Table 1. Calculated capacitance (μF/km)

single conductor cross section(mm ²)	0.6/1 kV electrical cable				8.7/10 kV	
	PVC cable (VV, VLV)		XLPE cable (YJV, YJLV)		XLPE cable (YJV, YJLV)	
	single core	three round core	single core	three round core	single core	three round core
50	1.667	1.335	0.704	0.556	0.192	1.667
120	2.192	1.780	0.892	0.642	0.260	2.192
240	2.259	1.810	0.896	0.642	0.344	2.259

3.1.2. Inductance Calculation

As single-core cables of three phases are in parallel and closely placed, the distance between the cable centers S is two times of cable diameter D . The average inductance of the three-phase L is

$$L = (L_i + 2 \ln \frac{S}{r_c} + 0.462) \times 10^{-1} \quad (5)$$

The inductance of round three-core cable L is

$$L = (L_i + 2 \ln \frac{2D}{r_c}) \times 10^{-1} \quad (6)$$

In the formula: D is the outer diameter of cable(mm), r_c is the radius of single wire (mm), L_i is the inductance of single wire (mH/km) which could be found in the Book of Wire and Cable[2].

The calculated inductance of PVC cables and XLPE cables with 50 mm²、120 mm²、240 mm² single conductor cross-sectional area are shown in table 2.

Table 2. Calculated inductance (mH/km)

single conductor cross section(mm ²)	0.6/1 kV electrical cable				8.7/10 kV	
	PVC cable (VV, VLV)		XLPE cable (YJV, YJLV)		XLPE cable (YJV, YJLV)	
	single core	three round core	single core	three round core	single core	three round core
50	0.491	0.248	0.486	0.234	0.601	0.366
120	0.459	0.232	0.456	0.223	0.547	0.318
240	0.447	0.230	0.441	0.221	0.514	0.290

3.1.3. The charging current and dielectric loss calculation

Due to the existence of the capacitance between the insulated cores, the charging current is generated during the operation, causing the dielectric loss. Because of the higher operating voltage of the XLPE cable, the charging current and dielectric loss are higher than the PVC cable.

The charging current of PVC cable is

$$I_c = U_0 kC = 0.1884C \quad (7)$$

XLPE cable charging current is

$$I_c = U_0 kC = 2.732C \quad (8)$$

In the formula: C is the capacitance of the cable (F/km)

The calculated charging currents of two types of electrical cables are shown in table 3.

Table 3. Calculated charging current (A/km)

single conductor cross section(mm ²)	0.6/1 kV electrical cable				8.7/10 kV	
	PVC cable (VV, VLV)		XLPE cable (YJV, YJLV)		XLPE cable (YJV, YJLV)	
	single core	three round core	single core	three round core	single core	three round core
50	0.314	0.251	0.133	0.105	0.524	0.524
120	0.413	0.335	0.168	0.121	0.711	0.711
240	0.426	0.340	0.169	0.121	0.940	0.940

When the cable is running, the active power consumed in the insulation, that is, the dielectric loss is calculated as follows:

$$W_T = U_0 kC \tan \delta \quad (9)$$

In the formula: U_0 is the voltage between cable and ground (V), C is the capacitance of the cable (F/km), $\tan \delta$ is tangent of dielectric loss angle, which is 0.1 for PVC cable and 0.008 for XLPE cable.

The calculated dielectric loss of two types of electrical cables are shown in table 4.

Table 4. Calculated dielectric loss (W/km)

single conductor cross section(mm ²)	0.6/1 kV electrical cable				8.7/10 kV	
	PVC cable (VV, VLV)		XLPE cable (YJV, YJLV)		XLPE cable (YJV, YJLV)	
	single core	three round core	single core	three round core	single core	three round core
50	18.8	15.1	7.96	6.29	36.5	36.5
120	24.8	20.1	10.1	7.25	49.5	49.5
240	25.5	20.4	10.1	7.26	65.4	65.4

3.1.4. Wire and cable impedance AC resistance calculation

The formula for calculating the AC resistance of the wire is as follows:

$$R = R_{20} [1 + T_{20} (\theta - 20)] (1 + y_s + y_p) \quad (10)$$

In the formula: R_{20} is the direct current resistance of the wire under 20°C, T_{20} is the temperature coefficient of the wire, which is $3.93 \times 10^{-3} / ^\circ\text{C}$ for copper wire, θ is the operation temperature of wire, y_s is the coefficient of the skin effect, y_p is the coefficient of the proximity effect.

According to standard products, when calculating AC resistance, θ of PVC cable is 70°C, and θ of XLPE cable is 90°C, the result is shown in table 5.

Table 5. Calculated AC resistance (Ω/km)

single conductor cross section(mm ²)	0.6/1 kV electrical cable				8.7/10 kV	
	PVC cable (VV, VLV)		XLPE cable (YJV, YJLV)		XLPE cable (YJV, YJLV)	
	single core	three round core	single core	three round core	single core	three round core
50	0.463	0.463	0.494	0.494	0.494	0.494

120	0.184	0.184	0.196	0.196	0.196	0.196
240	0.0911	0.0918	0.0973	0.0976	0.0972	0.0978

Because the cable's capacitive reactance to ground is much larger than its inductive reactance, it can be ignored when calculating the cable impedance. The calculation formula is:

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + 0.0986L^2} \quad (11)$$

In the formula: R is the AC resistance (Ω/km), L is the inductance (mH/km).

The calculated cable impedance of two types of electrical cables are shown in table 6.

Table 6. Calculated cable impedance (Ω/km)

single conductor cross section(mm^2)	0.6/1 kV electrical cable				8.7/10 kV	
	PVC cable (VV, VLV)		XLPE cable (YJV, YJLV)		XLPE cable (YJV, YJLV)	
	single core	three round core	single core	three round core	single core	three round core
50	0.488	0.470	0.517	0.499	0.529	0.507
120	0.234	0.192	0.242	0.208	0.260	0.220
240	0.167	0.117	0.138	0.120	0.189	0.134

0.6/1kV PVC or XLPE cables are usually five-core cables. Each cable has five metal wires, three of which are A, B, and C phase wires, one is the neutral wire, and one is the protecting earthing wire. When calculating the impedance of five-core cables, neutral and protecting earthing wire are ignored, and only the three phase wires are used.

3.2. Impedance model of enclosed busbars

Enclosed busbars is the ideal power distribution equipment for modern high-rise buildings. With average electricity consumption of the unit building area surging, the traditional power distribution way of using insulating wire or cable is unable to meet power requirements. Thus, usage of enclosed busbars is imperative.

Due to the large current carrying capacity of enclosed busbar, large cross-section area and near phase distance of conductive rows, skin effect and proximity effect should be taken into account when calculating the AC resistance value.[3] Theoretically, to obtain the correct inductance, rectangular conductive bar of enclosed busbar should be regarded as split wires, then the geometric mean of their distance should be calculated.

3.2.1. AC resistance calculation of enclosed busbar

The calculation formula of the AC resistance of the busbar is as follows[4]:

$$R = \rho_{20} [1 + \alpha(T - 20)] \frac{K_j K_i l}{b \times h} \quad (12)$$

In the formula: R is the AC resistance(Ω), ρ_{20} is the resistivity of copper under 20°C and its value is $0.0179 \Omega \text{ mm}^2/\text{m}$, α is the temperature coefficient of copper conductive bar and its value is 0.00385, T is the working temperature of conductive bar($^\circ\text{C}$), l is the length of conductive bar(m), b is the thickness of rectangular conductive bar(mm), h is the width of rectangular conductive bar(mm), K_j is the skin effect coefficient, see table 7 for details, K_i is proximity effect coefficient and its value is 1.03.

Table 7. Skin effect coefficient

$b \times h$	6×30	6×40	6×50	6×60	6×80	6×110	6×150	6×200
K_j	1.015	1.026	1.04	1.055	1.00	1.15	1.21	1.25

By consulting the manufacturer of enclosed busbar, the thickness of conductive bar is 6 mm, and the width of bar is 140 mm. Therefore, the AC resistance of enclosed busbar is 0.0132 mΩ/m according to former formula.

3.2.2. Inductance calculation of enclosed busbar

The formula for calculating the inductance of the busbar is as follows[4]:

$$X = 0.1445 \log \frac{D_i}{D_z} \quad (13)$$

In the formula: X is the inductance of each phase conductive bar of the busbar (mΩ/m), D_i is the geometric distance between the conductive bars of each phase (mm), D_z is the geometric distance of the conductive bars. For rectangular conductive bar, $D_z = 0.224(b+h)$ mm.

The calculation method of D_i is as follows:

$$D_i = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{AC}} \quad (14)$$

In the formula: D_{AB} , D_{AC} , D_{BC} is the average geometric distance of the phases A, B and C conductive bars, and $D_{AB} = D_{BC} = 0.5 D_{AC}$. As the busway is enclosed, the width of the conductive bars is much larger than the thickness, thus the distance between the centrelines of the conductive bars of each phase cannot be regarded as the geometric average distance between the conductive bars. Actually, the conductive bar could be considered as a combination of n split conductive wires which are distributed in the central axis. According to the concept of geometric mean distance:

$$\begin{aligned} D_{AB} &= \sqrt[n \times n]{(D_{aa'} \cdot D_{ab'} \cdot \dots \cdot D_{an'}) (D_{ba'} \cdot D_{bb'} \cdot \dots \cdot D_{bn'}) \dots (D_{na'} \cdot D_{nb'} \cdot \dots \cdot D_{nn'})} \\ D_{AC} &= \sqrt[n \times n]{(D_{aa''} \cdot D_{ab''} \cdot \dots \cdot D_{an''}) (D_{ba''} \cdot D_{bb''} \cdot \dots \cdot D_{bn''}) \dots (D_{na''} \cdot D_{nb''} \cdot \dots \cdot D_{nn''})} \\ D_{aa'} &= b + A & D_{aa''} &= 2(b + A) \\ D_{ab'} &= \sqrt{D_{aa'}^2 + D_{ab}^2} = \sqrt{D_{aa'}^2 + \left(\frac{h}{n-1}\right)^2} & D_{ab''} &= \sqrt{D_{aa''}^2 + D_{ab}^2} = \sqrt{D_{aa''}^2 + \left(\frac{h}{n-1}\right)^2} \\ D_{ac'} &= \sqrt{D_{aa'}^2 + D_{ac}^2} = \sqrt{D_{aa'}^2 + \left(\frac{2h}{n-1}\right)^2} & D_{ac''} &= \sqrt{D_{aa''}^2 + D_{ac}^2} = \sqrt{D_{aa''}^2 + \left(\frac{2h}{n-1}\right)^2} \\ &\dots & &\dots \\ D_{an'} &= \sqrt{D_{aa'}^2 + D_{an}^2} = \sqrt{D_{aa'}^2 + \left[\frac{(n-1)h}{n-1}\right]^2} & D_{an''} &= \sqrt{D_{aa''}^2 + D_{an}^2} = \sqrt{D_{aa''}^2 + \left[\frac{(n-1)h}{n-1}\right]^2} \end{aligned} \quad (15)$$

In the formula: b is the thickness of conductive bar, h is the width of conductive bar, A is the thickness of the insulating layer between two adjacent conductive bars.

By consulting the manufacturer of enclosed busbar, the thickness of conductive bar is 6 mm, and the width of bar is 140 mm; the thickness of the insulating layer is 1.5 mm. Thus it could be calculated that $D_i = 46.6226$ mm, $D_z = 0.224(b+h) = 34.048$ mm, $X = 0.0197$ mΩ/m.

3.2.3. Impedance calculation of enclosed busbar

The impedance of enclosed busbar is:

$$Z = \sqrt{R^2 + X^2} \quad (16)$$

According to the results in 2.2.1 and 2.2.2, the calculated impedance is 0.0237 mΩ/m.

3.3. Impedance model of transformer

3.3.1. Impedance calculation of transformer

The short-circuit loss of transformer is approximately equal to the total copper loss of the high and low voltage windings when the rated current flows through the transformer. For the three-winding transformer, only the maximum short-circuit loss $P_{k,max}$ is given, which is the loss as the rated current flows in two 100 % capacity windings, and the other winding is empty. The resistance R_T is calculate as follows[5]:

$$R_T = \frac{P_{k,max} U_N^2}{2000 S_N^2} \quad (17)$$

The reactance of transformer with large capacity is far greater than the resistance, so the transformer reactance is approximately equal the impedance in value. It can be concluded that the relationship between short-circuit voltage percentage $U_k\%$ and the reactance of the transformer is as follows[5]:

$$U_k \% \approx \frac{\sqrt{3} I_N X_T}{U_N} \times 100 \quad (18)$$

Then

$$X_T \approx \frac{U_N}{\sqrt{3} I_N} \times \frac{U_k \%}{100} = \frac{U_k \% U_N^2}{100 S_N} \quad (19)$$

In the formula: X_T is the total impedance of the high and low voltage winding (Ω), $U_k\%$ is the short-circuit voltage percentage, S_N is the rated capacity of transformer (MVA), U_N is the rated voltage of transformer (kV).

According to transformer test report[6], the impedance of 2000 kVA and 2500 kVA transformers are shown in table 8.

Table 8. Transformer impedance

Rated capacity S_N (kVA)	Maximum short-circuit loss $P_{k,max}$ (kW)	Winding resistance R_T (Ω)	Short-circuit voltage percentage $U_k\%$	Total impedance of the high and low voltage winding (Ω)
2000	15.691	3.138×10^{-4}	8.31	6.648×10^{-3}
2500	17.701	2.266×10^{-4}	8.17	5.229×10^{-3}

3.3.2. Excitation admittance calculation of transformer

The transformer iron loss P_{Fe} is approximately equal to the no-load loss P_0 , the transformer excitation conductance G_T can be calculated as follows[5]:

$$G_T = \frac{P_0}{1000 U_N^2} \quad (20)$$

As the transformer excitation susceptance B_T is much greater than the conductance, it may be considered that to the current flowing through the excitation susceptance I_b is approximately equal to the excitation current I_0 [5]:

$$I_0 = \frac{I_0 \%}{100} I_N = \frac{I_0 \%}{100} \cdot \frac{S_N}{\sqrt{3} U_N} \approx I_b = \frac{U_N}{\sqrt{3}} B_T \quad (21)$$

$$B_T = \frac{I_0 \%}{100} \cdot \frac{S_N}{U_N^2} \quad (22)$$

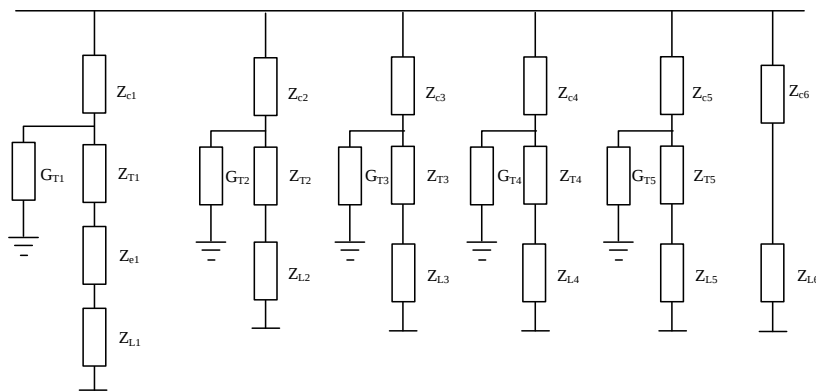
According to transformer test reports[6], the excitation admittance of 2000 kVA and 2500 kVA transformers are shown in table 9.

Table 9. Transformer admittance

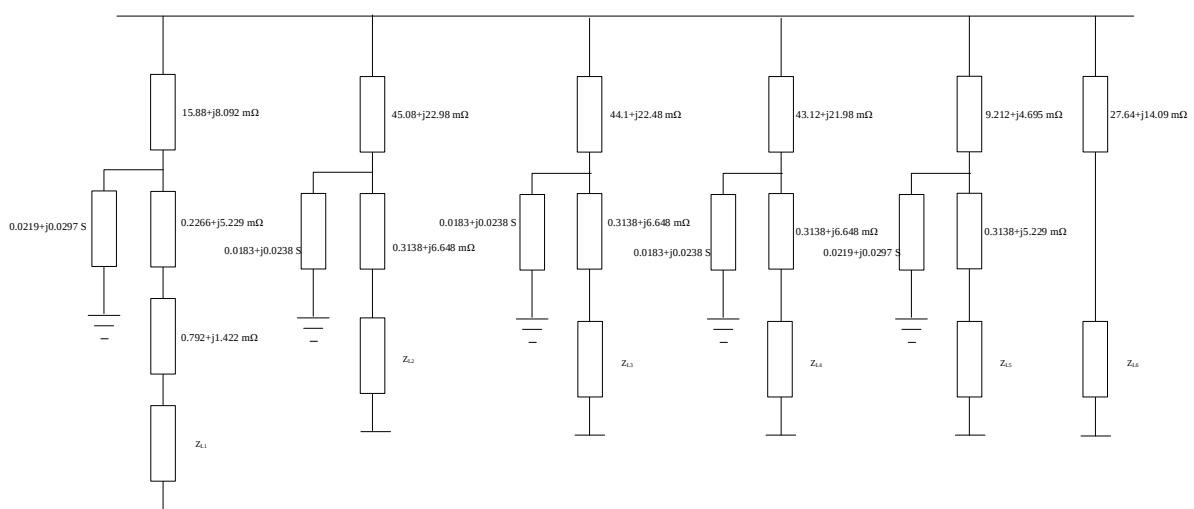
Rated capacity	No-load loss	Conductance	Excitation current percentage	Susceptance
S_N (kVA)	P_0 (kW)	G_T (S)	$I_0\%$	B_T (S)
2000	2.930	0.0183	0.19	0.0238
2500	3.505	0.0219	0.19	0.0297

4. Electrical model of power system in data center

We could get the electrical model of data center power system shown in figure 2. It should be noted that some parts of power system such as breakers are ignored because their impedances are too small. In figure 2, the Z_{c1} to Z_{c6} are the impedance of cables; Z_{T1} to Z_{T5} are the impedance of transformers; G_{T1} to G_{T5} are the excitation admittance of transformers; Z_{e1} is the impedance of enclosed busbar; Z_{L1} to Z_{L6} are the loads such as IT servers, electromotors or other building loads.

**Figure 2** Electrical model of Power System

By consulting the designer and builder of the data center, the actual specifications of electrical equipment are known. Then we could calculate the actual values of impedance, shown in figure 3.

**Figure 3** Impedance value of Power System

5. Conclusion

From the analysis above, we can establish the electrical model of data center power system which contains the impedances of cable, enclosed busbar and transformer. With the real parameters of former equipment, we can calculate the value of impedance.

By analysing the data center power system model, we get the theoretical value of electrical equipment impedance. When the power system is running, we can use electric meters or other equipment to measure electrical parameter values and find the actual impedance value. Comparing the calculated value and measured value of the impedance, we can get the status of the electrical equipment. For example, when the impedance measurement value is much larger than the calculated value, the device may have a poor contact.

6. References

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