Optimal design of converters and circuit breakers in high voltage substation system

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Abstract. Since most of replaceable resources generate the DC power or retrieve the most energy by converted to DC power and more DC loads are appearing on the market, the feasibility of low-voltage DC distribution has been discussed again recently. By applying DC distribution, conversions stages can be saved accompanied with benefits of high stability and the ease of designing UPS system. However, for nearly all distribution system is AC-powered at present, the feasibility of DC distribution system should be discussed. Moreover, AC/DC converters and DC breakers which are two important components in DC distribution system are also the issues to be discussed. Therefore, in this thesis, the feasibility of DC distribution will be investigated. In addition, the feasible topologies and design rules of converter and breakers are proposed with the verification by simulation results.

1. Introduction

In DC distribution, AC/DC converters and DC breakers are the key components in whole system. The converters should provide the function of voltage control on DC side and power factor correction on the AC side; while, DC breakers offer the protection against fault on the DC bus. To design the converters and breakers, the specification of voltage level of AC side and DC side should be decided first. Since there has not been a standard for low-voltage DC distribution, the specification is decided from a report of investigation in data centers utilized DC distribution[1].

For applying DC distribution, there are two key components, AC/DC converters and DC breakers. This thesis investigates the specification of converters suitable for applying in DC distribution system. In those converters, power losses are calculated as an index to compare their overall efficiency. Voltage control on the DC side and power factor correction on the AC side are also the primary requirements. Due to the absence of natural zero crossing current, the design of DC breakers is different from AC ones, therefore, in this thesis, the design rules of different DC breakers are investigated and their performance are also compared as a reference when selecting suitable DC breakers[2].

2. The utilized ratio between AC-fed and DC-fed loads

At present, AC distribution system is the only way to provide the electricity for residential and commercial facilities. Therefore, all electrical load, such as HVACs (heat, ventilation and air conditioning), lighting, households and office automation, can only operate by AC power[3].

For environmental issue drawing more attention recently, the demand for higher efficiency electrical facilities is urgent. Consequently, manufacturers begin to apply power electronic technique to enhance the efficiency and performance. As most power electronic technique relies on the use of power semiconductors which mostly possess forward blocking ability, power converters are required to operate by DC power. Cases are illustrated in the following subsections.
Air conditionings, washing machines, and refrigerator, etc. whose operation mainly rely on motor drives are typically driven by utility voltage and operate in run or stop two modes in coordination with constant speed motor. With the advance of power electronics, the manufacturers have been employing the technique of variable drives to enhance the efficiency. The circuit topology can be roughly illustrated by Figure 1[4].

![Front end circuit of variable motor drive under AC distribution](image1)

**Figure 1** Front end circuit of variable motor drive under AC distribution

DC distribution system, nowadays, has been applied to some fields for years. Due to more digital electronics and renewable energy application emerging to the market, the advantages of DC distribution over AC distribution have been discussed recently. Although loads at present are fed by AC voltage, most of them can be considered as DC without their individual rectifier at front end[5]. Therefore, the ratio between AC and DC loads are adjusted and the feasibility of applying DC distribution is reconsidered. The efficiency of DC distribution for different purposes has been discussed. From the view of load end, applying DC distribution can save conversion stages to enhance overall efficiency. From the view of generator end, DC distribution is superior if the amount of renewable energy occupies a large part of total energy consumption.

3. **Operation principles and simulation results of DC converters**

Simulations are presented to validate the effectiveness of rectified step-down voltage with PFC functionality in CSC. Steady-state and dynamic performance of are both examined by using simulation package“Electromagnetic Transient Program”[6]. Figure 2 shows the AC phase current operated in rated power. The peak value of phase current complied with theoretical value is close to 120 amperes. As indicated in Figure 3, the total harmonic distortion of phase current is calculated as 2.5%. To verify the functionality of PFC, the phase current is shown with phase voltage in Figure 4 as well as the power factor which is 0.99[7].

![Phase current at mains operated in rated power](image2)

**Figure 2** Phase current at mains operated in rated power
To achieve the advantages of high transmission efficiency in DC distribution system, the efficiency of converters used to convert AC power to DC power is considerable for overall efficiency. Therefore, the power loss in converters is one of the key factors to score the converters’ performance. Power loss in converters mainly consists of conduction loss and switching loss in transistors and diodes. The conduction loss results from the current through the transistors and diodes. The switching loss in transistor is turn-on and turn-off loss, while the switching loss in diode is mainly turn-off loss, i.e., reverse recovery energy. Due to the symmetry of AC feeding current and identical structure of the bridge legs, current stress of each leg is the same. Since one leg consists of one transistor and one diode and they are connected in series, their current average and rms values are equal[8].

In addition, the capacitance on the AC side has zero average current run through them. Therefore, the average current running through each leg can be expressed as a average of one half wave phase current within a period.

4. Operation Principles and Simulation Results of DC Breakers

In DC distribution system, the breaker is another key component besides the converter mentioned in the last chapter. However, the breaker design in DC distribution is not as simple as the mechanical breakers used in AC distribution due to the absence of natural zero crossing. In order to cut off direct current, other topologies of breakers applicable in DC environment have been investigated.

When ground fault occurred in DC bus, short-circuit current will increase rapidly due to the magnetization across line inductance caused by DC bus voltage. The design of DC breakers are required to demagnetize the short-circuit current on line inductance[9].

When the maximum tolerable voltage across the breaker increases beyond varistor’s break down voltage which is conventionally chosen to be 50% higher than the nominal grid voltage, the switch T is turned off. At this point, due to the sudden drop of current on line inductance, the induced voltage across it would increase very fast until the varistor started to conduct and clamped the voltage to demagnetize fault current to zero[10].
5. Conclusion
In this thesis, the feasibility of applying low-voltage DC distribution and the operation of its key components are discussed. The environmental feasibility of DC distribution discussed in this thesis shows that in the present structure of distribution system, DC power can be transferred without replacing the transmission facilities. In the case of data centers, DC distribution system is proved to have better efficiency than the best AC distribution system topologies. The efficiency of DC distribution utilized at home and in office building is also proved to be better than AC one with more DC loads and DC generators utilized in the future.

Therefore, a trade-off is needed to be made when selecting the converter. This thesis also showed the operations of four different DC breakers. The result indicated that solid-state DC breaker has the best performance. However, due to the conduction loss induced by the semiconductor within, the second choice, the circuit breaker with forced commutation is more suitable.

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