Summarization of busbar protection principle

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Abstract. Safe bus operation is an important requirement for stable power transmission of a power system. Further, bus protection is also an important part of relay protection. Regarding the former, a variety of different protection principles have been proposed. Based on the amount of protection used in different protection principles, this paper describes the advantages and disadvantages of power frequency protection, transient parameters protection, and full-waveform protection. Finally, the paper summarizes the problems to be solved by current bus protection and formulates its future research direction.

1. Introduction
Busbars are an important part of power plants and substations and they are responsible for the convergence and distribution of electrical energy. Once a busbar fails, the equipment connected to the busbar can be easily damaged, and in severe cases, even a large-scale blackout can occur. Therefore, it is of great significance to equip the busbar with a special protection device for a stably operating power system[1]. At present, except for some low voltage busbars that use the adjacent-component protection devices to cut off the busbar fault, a busbar is generally equipped with a special protection device[2].

The busbar protection device currently used mainly adopts the principle of current differential protection based on fundamental-frequency parameters[3-7]. Regarding the fault current of the busbar, the power frequency is a forcing part that will not decay over time. Therefore, it can correctly reflect the fault information; Owing to the strong attenuation of the high-frequency part caused by the stray capacitance of the busbar and the refraction of the traveling wave, the transient parameters are also used for bus protection[8]; The mature application of an electronic current transformer(CT) makes the acquisition of faulty full-waveform possible[9]. The full-waveform contains abundant fault information, which can determines fault without filtering[10]. This paper introduces various existing busbar protection principles and compares their advantages and disadvantages from multiple perspectives. Moreover it proposes new problems to be solved for the newly distributed protection method, and provides references for the future research.

2. Busbar protection based on fundamental frequency parameters
As a forcing component, the fundamental-frequency parameters have been widely used in the bus fault judgment due to their reliability. At present, there exist three main types of busbar protection that use the fundamental-frequency parameters: current phasor differential protection, current sample differential protection and parameter identification protection. Current phasor differential protection is the most widely used and reliable method[11-13].

2.1 Differential protection based on current phasor

Whether the differential protection of the current phasors, which is based on Kirchhoff’s current law, act or not, depends on the magnitude of the differential current in the differential current-loop[14]. As shown in Figure 1, the bus has n branches, here, we define

\[ I_d = I_1 + I_2 + I_3 + \ldots + I_n \]  

(2.1)

where \( I_d \) is the differential current of the busbar protection. Ideally, when the busbar operates normally or the fault is located outside the busbar, the differential current is zero and the busbar protection is inactive. When the fault lies in the busbar, its value is equal to the current flowing into the fault point, which is greater than the busbar protection set point, therefore, the protection will act. However, the CT of the fault branch will seriously saturate when the fault is located outside the busbar, resulting in misoperation. Proportional differential protection using braking characteristics is often applied in practice[15].

![Figure 1. Single-busbar system](image)

Proportional differential protection introduces the braking current \( I_r \), which is the sum of the amplitudes in the branches connected to the bus. The action current changes with the braking current. Thus, it can induce a certain degree of braking under out-of-zone fault condition. The criteria are as follows

\[ \begin{cases} 
I_d > I_{dset} \\
I_d > K \cdot I_r 
\end{cases} \]

(2.2)

where \( I_r = \sum I_j \) and \( I_d \) is the current of the j-th branch; \( I_{dset} \) is the set point of the differential current, which is determined by the maximum imbalance current under out-of-zone fault condition; \( k \) is the braking ratio which is related to protection sensitivity, its set value is influenced by the actual operating conditions. Figure 2 illustrates the operation characteristics of proportional differential protection.
Figure 2. Characteristic curve of proportional differential protection.

The protection method has a certain braking effect on out-of-zone faults. However, malfunction may occur when the faults occur in the busbar area, which may make protection unreliable. The Proportional differential protection of retriol adds a differential current to the braking current[16]. Thus the protection can act quickly when there is a fault in the busbar area, However, there still remains a strong braking behavior in the event of an out-of-zone fault. The action criterion can be expressed by the following

\[
\begin{align*}
I_d &> I_{\text{set}} \\
I_d &> K \cdot (I_i - I_d)
\end{align*}
\]

(2.3)

The operational process shows that the reliability and sensitivity of the protection can meet the actual needs of the power grid. The braking effect still only exists when a small ground fault current occurs in the busbar area.

In order to compensate for the shortcomings of traditional differential protection in terms of action speed, most microcomputer-based busbar protection devices are equipped with proportional differential protection components based on sudden current changes[17]. The rapid-action components of the busbar protection, which comprises dual protection implying traditional differential protection, enhances reliability and speed. Proportional differential protection for sudden current changes uses the instantaneous current variations of the differential current to set the action criterion. Thus, the protection is not affected by the power angle and the load state of the system power. Besides, it can further act quickly in the event of a resistive ground fault. This principle enhances protection sensitivity. The action criteria can be expressed as follows

\[
\begin{align*}
\Delta \sum_{j=1}^{n} I_j &> \Delta I_i + D I_{\text{set}} \\
\Delta \sum_{j=1}^{n} I_j &> K \sum_{j=1}^{n} |\Delta I_j|
\end{align*}
\]

(2.4)

where \( \Delta I_i \) is the power frequency variation current of the j-th branch, \( \Delta D I_i \) is the floating value for the differential current start and \( D I_{\text{set}} \) is the fixed value. The parameter K is the proportional braking coefficient of the power frequency variation.

Current differential protection is based on Kirchhoff's current law and the change of differential current can effectively reflect whether the busbar is faulty or not, it is a widely used protection principle in busbar protection devices of power plants and substations. However, there exist some problems in the actual operation, such as slow speed and CT saturation. Specifically, in the case of a transferring fault, the protection can not remove the fault quickly because of the blocking due to the saturation element.

2.2 Current differential protection based on sample value
The protection based on the phasor value only extracts the voltage and current signals of the power frequency to determine busbar faults. However, the data window used in the calculation of the phasor value is large. In general, one data cycle is needed and the action speed is not ideal. Reference [18] proposed using the sampled values to construct the differential protection criterion, conducting an evaluation for each sampling point. During evaluation of $S$ points—if there are $R$ times to satisfy the conditions—the protection acts such to achieve fast action. The action criteria are as follows

$$
\begin{align*}
\hat{i}_d(k) &> i_0 \\
\hat{i}_d(k) &> k\hat{i}_r(k)
\end{align*}
$$

where $\hat{i}_d(k)$ is the differential variable based on sample value, $\hat{i}_r(k)$ is the braking value and $i_0$ is the set point. Reference [19] conducted a theoretical study on the relation between the number of sampling points $S$ and the evaluation number $R$ necessary to be satisfied by the operation. The quantitative relation between $S$ and one sampling period $N$ is given and analyze the problem of differential protection in the fuzzy region in the complex plane. In reference [20], combined with sampling differential protection and CT saturation detection, the sampled value is evaluated in the linear transfer region of the predicted differential current. It not only can reliably block protection when the fault leads to CT saturation, but can also quickly act under the transferring fault. The differential protection based on sample values provides excellent protection against abnormal data and CT saturation. It has been applied in busbar differential protection, line differential protection and component protection. Among them, the application of component protection has been relatively mature[21-22]. However, with the movement of the sampling data window, a fuzzy protection zone exists and the theoretical analysis is based on the sinusoidal waveform which is different from the actual fault waveform. Therefore, it is difficult to ensure the reliable operation of the protection.

2.3 Parameter identification protection

The fault is often accompanied by a current rise and voltage decrease, while the current differential protection utilizes only the former. In the case of a nonmetallic fault, the differential current does not vary greatly and the sensitivity is significantly reduced. By adding fault information of voltage variations to the structural-parameter protection of the busbar, one can reduce the impact of transitional resistance on the sensitivity. Reference [23] analyzed the additional state of the fault and built the busbar inductance circuit model. According to the model parameters calculated in real time, its value can judge whether a bus fault occurred. The additional state of the bus fault, shown in figure 3

![Image of additional state of busbar fault](image)

**Figure 3.** Additional state of busbar fault

The next mode is equivalent to the additional state of the fault, as shown in figure 4

![Image of equivalent state](image)
Figure 4. Equivalent network of additional state

The parameter $L_{eq}$ is the line inductance calculated with the sampling points within a time period. When there is a fault in the busbar, due to the constraints of the busbar system model, the parallel branch has the impedance $Z = W L_{eq}$. Its value is relatively small and would not scale very well as time window goes on; for the fault outside busbar, due to the voltage and current constraints disappear, $Z$ is the actual capacitive reactance of the busbar against the ground and whose value scales very well over time. The simulation results show that the protection has a high sensitivity and reduces the effect of transition resistance and CT saturation. Based on the study with an additional network of busbar faults, the reference [24] used admittance parameters to identify faults. They added a fault voltage to the current differential protection to obtain the differential and brake admittance.

$$Y_d = \left[ \frac{\Delta I_1}{\Delta U_1} + \frac{\Delta I_2}{\Delta U_2} + \cdots + \frac{\Delta I_n}{\Delta U_n} \right]$$  \hspace{1cm} (2.6)

$$Y_s = \left[ \frac{\Delta I_1}{\Delta U_1} + \frac{\Delta I_2}{\Delta U_2} + \cdots + \frac{\Delta I_n}{\Delta U_n} \right]$$  \hspace{1cm} (2.7)

Differential admittance and brake admittance are equal when the fault occurs in the busbar. In the case of an out-of-zone fault, the differential admittance is formed by the stray capacitance of the busbar relative to the ground. The differential admittance is quite different from the braking admittance. Therefore the fault can be distinguished. The simulation results show that this method can effectively distinguish between faults inside and outside the busbar and reduces the effect of transition resistance greatly. Besides, the protection is not affected by the sampling synchronization of sampling at different intervals. This is very suitable for distributed busbar protection. In practical applications, it needs to cooperate with a traditional protection method for dual protection. Based on the positive and negative sequence model of a busbar, reference [25] calculated the positive and negative sequence current and voltage according to the branch current and voltage to determine the direction of positive and negative sequence impedances. In the event of a busbar fault, each branch detects the positive and negative sequence impedance in the opposite direction. In the case of an out-of-zone busbar fault, the positive and negative sequence impedances are detected in positive direction in the fault branch, and the nonfaulty branch is examined in negative direction. Simulation results show that this method can effectively reduce the effect of CT saturation and ratio imbalance. Nevertheless, the accuracy of the positive and negative sequence components is greatly affected by the data window used in the calculation. Parameter identification protection is not affected by the system operation state, transition resistance, and system oscillations. However, the accurate construction of the network model is difficult and is greatly influenced by the topology of the system network. Currently, it is still at an exploratory stage[26-27].

Traditional differential protection based on power frequency has been widely used in practical engineering applications. Due to the problems of CT saturation, brake blurring region, and transient resistance, the busbar protection devices are equipped with antisaturation components and dual protection that, to some extent, achieves bus protection. However, the time window for extracting the power frequency is longer. Owing to the saturation detection process, it is difficult to further improve the protection speed and to completely avoid malfunctions for out-of-zone faults.
3. Busbar protection based on transient component

The fault is often accompanied by the emergence of a transient component that is very difficult to extract before. The busbar protection is used to filter out high-frequency components and the fundamental-frequency parameters are applied for fault evaluation. Owing to the emergence of wavelet transform tools and the tremendous increase in computing power of hardware systems, transient information-based protection has been deeply studied. The protection of high-frequency transient parameters is mainly based on the effect of the busbar on the reflection and attenuation when the traveling wave passes. Then the traveling wave energy and direction are analyzed to distinguish whether the faults lie in inside or outside the busbar area.

Reference [28] firstly proposed that the wavelet transform can be used to extract the transient characteristics of the fault for power system analysis. Moreover, the transients were applied for busbar protection for the first time. The simulation results show that busbar protection based on transient information exhibits good selectivity and quick action speed. A new type of directional busbar protection is proposed in reference [29] with the assumption that the transient wave moves in positive direction when departing from the busbar towards the line. Regarding that line, its fault is positive and the busbar and other line faults lie in the opposite fault direction. When a fault occurs in the busbar area, only the forward-traveling wave can be detected at the exit of each line. This can be judged as a negative fault. In the event of an out-of-zone fault, the faulty branch can detect the backward- and forward-traveling waves that results from the reflection of a backward-traveling wave. The magnitude of the latter is small. The protection evaluates it as a positive fault. The nonfaulty branch has only the forward-traveling wave which is evaluated as a negative fault. According to the characteristics of a forward-traveling wave and anti-traveling wave at different fault locations, a criterion can be constructed to identify the bus fault. However, there exists electromagnetic coupling between the three phases. In order to eliminate the influence, phase-shift transformation is also required to extract the line mode component for protection judgment. Reference [30] used the direction of the traveling power wave to determine bus faults and to define the power

\[ S_k = u_k \times i_k \]  

where \( k (= 1,2,3, ..., n) \) is the line number. Assuming that the positive direction of the traveling power wave is from bus to line, when a fault occurs in the bus, the initial traveling voltage and current waves have the same polarity so that there are \( S_k > 0 \) and a positive power direction. When an external fault occurs, when a fault occurs in the bus, the initial traveling voltage and current waves have the same polarity so that there are \( S_k > 0 \) and a positive power direction. the power direction is negative, and the power direction of the nonfaulty line is positive. Considering the different power directions, the bus fault can be determined. In reference [31], the decay effect of busbar-equivalent capacitance relative to the ground under a high frequency signal and the instantaneous amplitude of the traveling wave at the exit of each line are extracted for evaluation. When there is a fault in the busbar area, the amplitude of the transient traveling wave detected at each exit is very large. However, for an out-of-zone fault, only the amplitude of the traveling wave of the faulty branch is larger and the magnitude of the other branch is small due to the equal capacitances. In addition, the initial fault angle and transition resistance have great impact on the protection. They need to be measured and then reunified, or machine learning methods have to be applied to achieve Intelligent transient protection[32].

The use of transient information for busbar protection not only enables rapid fault removal, but also suppresses CT saturation. In order to reliably distinguish between the busbar faults, the judgment of protection is usually done with the integral value of a short time period to improve the protection reliability. However, there exist some problems with the protection of transient information. If the phase voltage crosses zero when the fault happens, the protection will not act because of the lack of transient information. The transient information caused by lightning and switch operation may cause a protection error. The transition resistance and the initial fault angle will also affect the judgement of protection. At present, the busbar protection based on traveling wave is still at the stage of theoretical exploration. Traveling-wave protection is only applied to HVDC transmission lines, and the correct
The differential value, $S_d$, is the braking value, and $I_0$ is the set point. A protection based on transient and full-wave protection is deeply studied and the reliability of full-wave protection is analyzed.

The application of OCTs not only makes the extraction of transient information more accurate, but also promotes the research of the full-wave protection. Compared with the fundamental frequency protection, the study of full-wave protection is still in its infancy, and there is a game between its quickness and selectivity. To better deal with their relation, the design of reliable protection methods based on the fault type, transition resistance, and other factors is necessary.

5. Focus and recommendations on future busbar protection methods
The principle of busbar protection can be divided into: fundamental-frequency parameters protection; transient-parameters protection; full-waveform protection depending on the protection parameters. Among them, the fundamental-frequency protection algorithm is the most mature and has been widely applied. Although the transient-parameter protection is limited by the saturation factor of the traditional CT, full-waveform protection is still in the early stages of research. It relies on the full-waveform current of faults collected by OCTs. These busbar protection principles have their own characteristics. Specifically, the protection based on transient and full-waveform parameters which can achieve rapid protection action and improve the stability of the power system. Research on nonfundamental frequency protection has a huge development prospective and research significance. The following are the fields that need further study for busbar protection.

(1) The proposal of "localized protection" makes the busbar protection mode extend towards the...
modular design and each protection unit exchanges the data through the private network. Traditional centralized busbar protection is going to be replaced by distributed busbar protection, which also introduces new problems to busbar protection\[38\]. Transmission delay caused by wireless communication and nonsynchronization sampling caused by sampling at different intervals will cause protection malfunction. It is very important to study the principles of busbar protection that will not be affected by data synchronization for future busbar protection.

(2) On must study the factors that affect the reliability of the transient-parameter protection and find out the difference between the fault transient parameters and the nonfaulty transient parameters caused by the switching operation and lightning strike. Further, a study on how to output the fast lockout signal, the effect of the transition resistance and the initial fault angle on protection must be conducted. Full advantage must be taken of the characteristics of fast action of transient-parameters protection. Moreover, the cutting time has to be reduced and the stability of the power system must be improved.

(3) The busbar protection method based on full-waveforms must be investigated and a full use of all fault information contained in the full-waveform to design an algorithm with superior protection performance must be made. Based on the OCTs, differential protection calculation directly on the optical path must be studied to avoid data error and loss caused by electromagnetic interferences. To ensure selectivity, rapid protection must be achieved.

6. Conclusion
In this paper, busbar protection is divided into fundamental-frequency parameter protection, transient-parameter protection and full-waveform protection depending on the protection parameters. The advantages and disadvantages of these busbar protection methods are summarized. In the future, the new problems encountered in busbar protection must be analyzed and the research focus of busbar protection needs to be discussed.

References
[1] Yu Huai S. 2008 ,Power system protection principle [M].China Electric Power Press.
[2] LiBing. 2016, Comparative analysis of busbar protection for various voltage levels, Electrotechnical Engineering 8 52–3
[3] Lu H, Wang F, Bao K and Li L. 2012 , General busbar protection device for PCS-915 series busbar protection devices Automation of Electric Power Systems 36 16 118–23
[4] Wang Y, Wu J and Guo H. 2006, Application of SG B750 digital bus protection device Human Electric Power 05 p 55-57+60
[5] Tang P, Chen Y, Xia J, Ma T and Chen D. 1996, Development of microcomputer type busbar protector Electric Power Automation Equipment 04 37–41
[6] Huang H, Cao Y and Bai Y. 2011, Analysis and treatment of BP-2P busbar protection device operation accident Electrotechnical Engineering 07 7–8
[7] Song X, Yu Z, Tu D, Cheng T and Wang D. 2000, Research on a new generation of microcomputer busbar protection device for WMH-800 Relay 11 39–41
[8] Hu Y. 2015, Research on transient quantities based on bus protection research Electrotechnical Engineering: Theory and Practice 11 222
[9] Guo Z. 2005, Review of electronic current transformer research Relay 14 11–14 + 22
[10] Yu W, Zhang G, Guo Z. 2015, Full-waveform integral-type current differential protection Proceedings of the CSU-EPSA
[11] Song F, Wang Z and Liu Y. 2003, General status and development trend of busbar protection Electric Power Automation Equipment 07 66–69
[12] Yao B and Xu T. 2003, Several busbar protection principle and operation analysis Hubei Electric Power 02 23–25
[13] Wang Y and Qiu Z. 2007, Status and development of bus protection principle Ningxia Electric Power S1 75–78
[14] Jia X. 2015, Analysis of substation bus current differential protection principle and precautions Engineering Technology: Digest 10 00131
[15] Suonian J, Zhang Y and Jiao Z. 2006, A current differential protection based on fractional ratio braking Automation of Electric Power Systems 17 54–58 + 75
[16] Lin X, He Z, Liu S, Yang C and Liu P. 2001, Reliability evaluation of proportional differential protection criteria Proceedings of the CSEE 07 99–103
[17] Bian N, Li N and Wu L. 2013, New criterion and simulation validation of differential protection based on sudden change Chinese Society of Electrical Engineers Young Academic Conference
[18] Yuan R, Chen D and Ma T. 2000, Study on the principle of current differential protection of sampled value Electric Power Automation Equipment 20 1–3
[19] Yang J, Yin X, Chen D, Zhang Z and Hu Y. 2003, Study on the operating characteristics of sampled value differential protection Proceeding of the CSEE 09 p 71–77
[20] Fan J, Man C, Sun M. 2017, A differential protection method for bus sampled value based on the current transfer region of current transformer: CN106602521A[P].
[21] Hu Y, Chen D, Yin X, et al. 2000, Sampling differential and its application Automation of Electric Power Systems 24 10 40–44
[22] Zhang Z, Liu H, Yue W and Xi W. 2011, Application of sampling value differential in line differential protection Automation of Electric Power Systems 35 12 76–79
[23] Suonian J, Deng X, Song G and Jiao Z. 2010, General principle of busbar protection based on model parameter identification Proceedings of the CSEE 30 22 92–99
[24] Yang C, Song G, Yang Y and Xu H. 2017, A new principle of distributed busbar protection based on admittance parameter identification Electric Power Automation Equipment 37 03 107–14
[25] Sachdev M S, Sidhu T S and Gill H S. 2000, A busbar protection technique and its performance during CT saturation and CT ratio-mismatch IEEE Transactions on Power Delivery 15 3 895–901
[26] Suonian J, Kang X, Song G, et al. 2007, Research on relay protection principle based on parameter identification Acta Behavioral Automation System 19 1 14–20 +27
[27] Suonian J, Wang Z, Zhong Y, Yao X, Chen X and Kang X. 2013, Protection algorithm of long distance transmission line grounding distance based on parameter identification High Voltage Engineering 39 11 2814–21
[28] Jiang F, Bo Z Q, Redfern M A, Weller G, Chen Z and Xinzhou D. 2001, Application of wavelet transform in transient protection-case study: busbar protection Seventh International Conference on Developments in Power System Protection (IEE) (Amsterdam) p 197–200
[29] Liu D. 2016, A new type of directional busbar protection principle and the realization of technology (Shandong University)
[30] Duanjian D, Zhang B and Zhang S. 2004, Distributed busbar protection using power direction of transient traveling waves Proceedings of the CSEE 6 06 11–16
[31] Guo Z. 2015, Based on the initial fault angle and transition resistance of the line bus transient protection method (Hunan University)
[32] Zhenwei G, Jiangang Y, Yuechun J, Xiangqian Z, Zhewen T and Wu W. 2015, A novel distributed unit transient protection algorithm using support vector machines Electric Power Systems Research 123 13–20
[33] Zheng W, Zhang N, Yang G et al. 2015, Comparison and improvement of traveling wave protection for Siemens and ABB DC lines Power System Protection and Control 24 149–154
[34] Li A, Cai Z, Li X, et al. 2010, Analysis and improvement of influence factors of traveling wave protection in HVDC transmission lines Automation of Electric Power Systems 34 10 76–80
[35] Qu Y. 2005, Application of optical current transformer in relay protection (North China Electric Power University (Hebei))
[36] Yu W, Zhang G, Guo Z, Song P and Huang H. 2015, Full waveform integral current differential protection News & Transactions of the Chinese Society for Electric Power Systems and Automation 27 09 69–73
[37] Yue K. 2016, A new type of line differential protection based on optical current transformer (Harbin Institute of Technology (Heilongjiang))

[38] Liu W, Ni C, Yang H et al. 2011, Implementation scheme of distributed busbar protection in intelligent substation *Power System Protection and Control* **39** 16 139–141 +146