2005 IEEE/PES Transmission and Distribution
Conference & Exhibition: Asia and Pacific
Dalian, China

Research of Traveling-wave Differential Bus Protection Based on Wavelet Transform

DUAN Jian-dong, ZHANG Bao-hui, *Senior Member, IEEE*, and LUO Si-bei

***Abstract*--To avoid the adverse effect of current transform (CT) transient saturation, this paper studies a novel bus protection based on transient current traveling-waves. Firstly the paper presents the differential traveling-wave (DTW) for each phase of circuits connected to the protected bus. The DTW fault features are analyzed. Then in order to distinguish more sensitively between faults internal and external to the bus, the restraint traveling-wave is introduced into the DTW. Thus the paper proposes the bus protection of differential traveling-waves with the restraint characteristic, and advances the practicable protection algorithm using the wavelet transform. The theoretical analysis and EMTP simulation tests show that the bus protection operates rapidly, sensitively and reliably, and that its performance can endure the influences of various fault path resistances, fault inception angles, fault locations and fault types.**

***Index Terms*--Bus protection, CT saturation, differential, restraint, traveling wave, wavelet transform**

I. Introduction

A bus is an energy concentration and distribution point in electric power systems. A single bus fault is equivalent to many simultaneous faults, and usually results in catastrophic failures such as equipment damage, system instability, and service interruption. In order to lessen the damaging effects of bus faults, high-speed and reliable bus protection is required.

The hitherto proposed algorithms of bus protection, mainly based on power-frequency components, do not possess inherent immunity to current transform (CT) saturation [1]. The performance of these bus protection algorithms is improved by using other additional measures. Unfortunately, these measures are likely to not be effective during severe CT saturation, and reported to result in other impact such as reducing relay sensitivity and delaying trip times. In fact, if the traveling-wave or transient information from the inception of the fault to the onset of CT saturation is used, the bus protection performance will be immune to CT saturation, which is the basic purpose to study transient-based bus protection.

Reference [2-3] presented the same type of bus protection, which is achieved by means of comparing the polarity or direction of current traveling-waves on circuits connected to the bus. These protection schemes maybe mal-operate when there is light faults occurring on a circuit. As well known, the differential protection is one of the popular bus protection schemes, which are mainly based on power-frequency components. However, the differential scheme for protecting buses based on fault traveling-waves has not been investigated yet.

Limited by the signal-processing tools, it has been difficult to extract and represent of traveling-wave information. With the advent of wavelet transform, the analysis of traveling waves becomes feasible and convenient. Unlike traditional Fourier transform, a wavelet transform is able to simultaneously provide the time and frequency information of signals [4]. This ability can be well adapted for exactly finding the fault time and spatial distribution of a singular signal. Wavelet transform has successful applications in many fields of power systems, including fault location [5], high-impedance fault detection [6], power quality detection and classification [7], etc.

This paper studies a new-type bus protection based on traveling-waves, and presents the differential protection criterion with the restraint characteristic. The wavelet transform is used to analyze traveling waves and achieve the practicable bus protection algorithm. A large number of EMTP simulation tests are conducted, and the results demonstrate that the new bus protection scheme is feasible.

II. Principle And Algorithm

A. Traveling-wave Fault Features

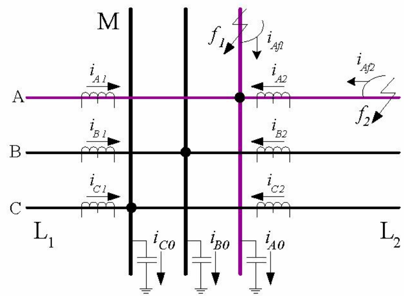

Fig. 1. Three-phase diagram of bus system

Fig.1 depicts a typical bus system of three-phase high voltage power systems. When a fault occurs on the bus or its circuits such as fault f_1 or f_2, the fault transient traveling-waves will propagate from the faulty point. Because of electro-magnetic coupling, there also exist fault traveling-waves in

Project supported by National Natural Science Foundation of China (50277027) and the XUJI Bounty of China Electricity Fund.

DUAN Jian-dong, ZHANG Bao-hui and LUO Si-bei are all with the school of Electric Engineering, Xi'an Jiaotong University, China (e-mail: duanjd@mail.xjtu.edu.cn).

non-fault phase. For each phase in bus zone, one part of fault traveling-waves, marked with $i_{\phi 0}$, will flow into ground through the stray bus capacitor (generally 2000~15000pF)[8], where ϕ denotes phase A, B or C. The other part of fault traveling-waves, marked with $i_{\phi m}$, will propagate along the circuits, where $i_{\phi m}$ is the current traveling-wave in phase ϕ of m-th circuit (m = 1,2,é ,n) and the currents entering the bus is considered to be positive.

Let the differential traveling-wave

$$i_{\phi d}=\left|\sum_{m=1}^{n} i_{\phi m}\right|=\left|i_{\phi 1}+i_{\phi 2}+\cdots+i_{\phi m}+\cdots+i_{\phi n}\right| \tag{1}$$

Table 1 shows the $i_{\phi d}$ expressions in the presence of bus or circuit fault.

TABLE I

FAULT FEATURES OF $i_{\phi d}$

	Faulty phase $i_{\alpha d}$	Healthy phase $i_{\beta d}$
Fault on bus	$\left|-i_{\alpha f}+i_{\alpha 0}\right|$	$\left|i_{\beta 0}\right|$
Fault on circuit	$\left|i_{\alpha 0}\right|$	$\left|i_{\beta 0}\right|$
where α and β denote faulty, healthy phase respectively, and $i_{\alpha f}$ is the traveling-wave in faulty phase when a fault occurs on bus.		

Generally speaking, $\left|-i_{\alpha f}+i_{\alpha 0}\right| >> \left|i_{\alpha 0}\right|, \left|i_{\beta 0}\right|$, therefore $i_{\alpha d}$ with high magnitude is fairly meaning for distinguish bus fault from circuit fault. However, when a fault on bus is very light, the differential traveling-wave $i_{\alpha d}$ of faulty phase will become small, even $i_{\alpha d}=\left|-i_{\alpha f}+i_{\alpha 0}\right|$ is less than $\left|i_{\beta 0}\right|$ of severe circuit fault.

In order to ensure the selectivity between light bus fault and severe circuit fault, the paper introduces a restraint traveling-wave component $i_{\phi r}$. The restraint traveling-wave will impose restraint effect on differential traveling-wave $i_{\phi d}$ in the case of circuit faults, but not in the case of bus faults. The restraint traveling-wave $i_{\phi r}$ here is chosen as

$$i_{\phi r}=\sum_{m=1}^{n}\left|i_{\phi m}\right|=\left|i_{\phi 1}\right|+\left|i_{\phi 2}\right|+\text{é}\ \left|i_{\phi m}\right|+\text{é}\ +\left|i_{\phi n}\right| \tag{2}$$

It is not difficult to analyze that the restraint traveling-wave of faulty phase $i_{\alpha r}=i_{\alpha d}$ only in presence of bus fault, but in other cases $i_{\alpha r}>i_{\alpha d}$ and $i_{\beta r}\geq i_{\beta d}$, no matter the fault is light or severe.

Considering the differential traveling-wave $i_{\phi d}$ associated with the restraint effect of $i_{\phi r}$, the paper forms the ratio

$$k_{\phi}=i_{\phi d}/i_{\phi r} \tag{3}$$

The fault features of ratio k_{ϕ} are shown in table 2.

TABLE II

FAULT FEATURES OF RATIO k_{ϕ}

	Faulty phase	Healthy phase
Fault on bus	$k_{\phi}=1$	$k_{\phi}\leq 1$
Fault on circuit	$k_{\phi}<1$	$k_{\phi}<1$

B. Bus Protection Principle

From Table 2, it can be seen that there is obvious difference between bus fault and circuit fault, i.e., the ratio k_{ϕ} of at least one phase is equal to 1 only when a fault occurs on the bus. Accordingly, the new bus protection principle is proposed as follows,

A) If at least one phase $k_{\phi}>K$, then the fault is determined to be on bus;

B) If $k_{\phi}\leq K$ for all three phases, then the fault is determined to be on some circuit.

where k_{ϕ} is computed through equation (3), and K is a preset threshold whose value is near to 1.

In nature, the bus protection above is in terms of current traveling-wave differential principle, and k_{ϕ} implies the effect of restraint traveling-wave, so it is called traveling-wave differential bus protection with restraint characteristic.

The introduction of restraint traveling-wave enhances the selectivity and reliability of differential principle. Moreover, the comparison of ratio k_{ϕ} with threshold K is actually to compare the differential traveling- wave $i_{\phi d}$ with a floating threshold $K i_{\phi r}$ under different fault conditions, hence to a great extent the new bus protection is adaptive.

C. Bus Protection Algorithm Using WT

In the foregoing bus protection, it is very fundamental to properly extract and represent fault traveling waves. A fault traveling-wave signal is high frequency and embodied with much sudden-change. With respect to Fourier transform, the wavelet transform (WT) is fairly suitable to analyze this kind of non-steady traveling-wave signal, because it possesses the property of time-frequency localization and multi- resolution decomposition.

The wavelet $\psi(t)$ based on B-spline function $N_m(t)$, $\psi(t)=\frac{d}{dt}N_m(t)$ is gradually optimal to detect and represent singular signals, so the paper chooses the dyadic wavelet transform (DWT)

$$(W_{2^j}f)(t)\ ;\ \frac{d}{dt}[f(t)*N_m(\frac{t}{2^j})] \qquad \text{scale } j\in\mathbf{Z} \tag{4}$$

to analyze the fault-induced transient signals. The DWT (4) can extract the desired frequency-band traveling-wave from fault transient signal, determine the sudden-change time of traveling-wave front and represent the sudden-change value with the wavelet transform maxima (WTM). Other details about wavelet transform can be referred to in [4].

Using the wavelet transform, the current traveling waves in Equation (1), (2) and (3) can be represented with their WTMs. Then the traveling-wave differential bus protection algorithm is designed as:

Step1. To capture faulty current signals from each circuit connected to the protected bus, and derive model signals from phase ones with Clarke transform;

Step2. To wavelet transform the model signals, and find their WTMs;

Step3. To calculate $i_{\phi d}$ and $i_{\phi r}$ with the WTMs, then obtain $k_\phi = i_{\phi d} / i_{\phi r}$ of corresponding phase ϕ (A, B or C);

Step4. To identify the fault internal or external to the bus protection zone, let the threshold value K= 0.85,

- If $k_\phi > K$ in at least one phase, the fault is determined to be internal;
- If $k_\phi \le K$ in all three phases, the fault is determined to be external.

III. EMTP Simulation Tests

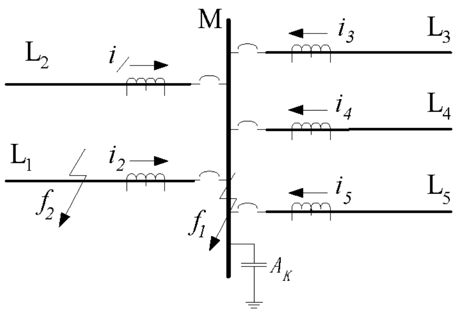

Fig.2. Configuration of the Studied Bus

A bus and its circuit in an existing 500kV substation is shown in Fig.2. Bus M is LGJQT-1400 type, 90m long, and its inductance/capacitance matrix [9] is

$$L=\begin{bmatrix} 8.9685 & 2.0290 & 1.2283 \\ 2.0290 & 8.9685 & 2.0290 \\ 1.2283 & 2.0290 & 8.9685 \end{bmatrix} \mu H/m,$$

$$C=\begin{bmatrix} 1.3187 & -0.2714 & -0.1192 \\ -0.2714 & 1.3638 & -0.2714 \\ -0.1192 & -0.2714 & 1.3187 \end{bmatrix} pF/m$$

The circuits L_1~L_5 are practical transmission lines (*J. Marti* frequency-dependant model). EMTP simulates transients of bus fault f_1 or line L_1 fault f_2. The signal sampling-rate is 400kHz, and the data window is 1*ms*.

The performance of the differential traveling-wave bus protection based on the wavelet transform is evaluated with the EMTP simulation data under various fault conditions of different path resistances *R*, inception angles θ, fault types and fault locations from bus M. Part of test results are illustrated in Table 3-6, where the WTM $i_{\phi d}$, $i_{\phi r}$ and ratio k_ϕ are calculated at scale 2 of wavelet transform. *Ag* means phase-A-to-ground short-circuit fault.

The test results indicate that it is rather apparent to discriminate the faults internal and external to the bus zone, and the proposed protection algorithm is fast and reliable under the variety of the fault conditions.

IV. Conclusions

The paper proposes the traveling-wave differential bus protection with restraint characteristic, which is essentially immune to CT transient saturation due to using the faulty information of the traveling waves. And the paper presents the applicable bus protection algorithm based on wavelet transform. Numerous EMTP simulation tests show that the novel bus protection can operate rapidly and reliably, and that its performance can endure the influences of various fault situations such as fault type, fault path resistance, etc.

V. Acknowledgement

The authors would like to thank the valuable support of the National Natural Science Foundation of China and the XUJI Electrical Group Company.

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TABLE III

BUS PROTECTION RESPONSE TO FAULTS WITH DIFFERENT FAULT PATH RESISTANCES ($Ag, \theta = 20^0$)

Fault location	Fault resistance	Phase A			Phase B			Phase C			Identifying results (k_{ϕ}>K=0.85?’	
		i_{Ad}	i_{Ar}	k_A	i_{Bd}	i_{Br}	k_B	i_{Cd}	i_{Cr}	k_C		
Bus M	500Ω	368.3	368.3	1	0.95	5.09	0.19	1.43	12.6	0.11	k_A>K	internal fault to the bus
	100Ω	1241.2	1241.2	1	3.97	3.97	1.0	1.96	16.8	0.12	k_A>K	
	1Ω	2887.0	2887.0	1	8.43	8.43	1.0	2.55	21.45	0.12	k_A>K	
Line L_1 (20km away)	500Ω	0.32	256.2	0.001	0.21	110.0	0.002	2.25	139.8	0.016	k_{ϕ}<K	external fault to the bus
	100Ω	0.80	664.9	0.001	0.55	277.4	0.002	5.28	358.4	0.014	k_{ϕ}<K	
	1Ω	1.31	1071.8	0.001	1.05	444.3	0.002	7.82	579.5	0.014	k_{ϕ}<K	

TABLE IV

BUS PROTECTION RESPONSE TO FAULTS AT DIFFERENT INCEPTION ANGLES ($Ag, R = 200\Omega$)

Fault location	Inception angle θ	Phase A			Phase B			Phase C			Identifying results (k_{ϕ}>K=0.85?’	
		i_{Ad}	i_{Ar}	k_A	i_{Bd}	i_{Br}	k_B	i_{Cd}	i_{Cr}	k_C		
Bus M	90^0	2213.1	2213.1	1	59.1	252.3	0.23	33.7	358.3	0.09	k_A>K	internal
	45^0	1633.7	1633.7	1	3.98	8.28	0.48	5.35	19.0	0.28	k_A>K	
	1.1^0	45.6	45.6	1							k_A>K	
Line L_1 (20km away)	90^0	1.62	1345.5	0.001	1.12	561.8	0.002	10.8	725.1	0.01	k_{ϕ}<K	external
	45^0	1.21	1007.5	0.001	0.84	420.8	0.002	8.19	542.8	0.02	k_{ϕ}<K	
	2.1^0	0.58	56.4	0.01	0.54	27.9	0.02	0.57	30.6	0.02	k_{ϕ}<K	

TABLE V

BUS PROTECTION RESPONSE TO FAULTS AT DIFFERENT LOCATIONS ON LINE L1 ($Ag, R = 200\Omega, \theta = 20^0$)

Fault location	Distance from bus M	Phase A			Phase B			Phase C			Identifying results (k_{ϕ}>K=0.85?’	
		i_{Ad}	i_{Ar}	k_A	i_{Bd}	i_{Br}	k_B	i_{Cd}	i_{Cr}	k_C		
Line L_1	150km	5.75	229.3	0.025	14.6	200.2	0.073	23.6	114.7	0.21	k_{ϕ}<K	external
	75km	18.9	235.2	0.080	5.82	235.8	0.024	18.1	273.0	0.066	k_{ϕ}<K	
	1.0km	0.89	757.8	0.001	3.59	24.2	0.15	5.98	29.6	0.20	k_{ϕ}<K	

TABLE VI

BUS PROTECTION RESPONSE TO DIFFERENT TYPES OF FAULT ($R = 200\Omega, \theta = 20^0$)

Fault location	Fault type	Phase A			Phase B			Phase C			Identifying results (k_{ϕ}>K=0.85?’	
		i_{Ad}	i_{Ar}	k_A	i_{Bd}	i_{Br}	k_B	i_{Cd}	i_{Cr}	k_C		
Bus M	Ag	774.8	774.8	1	0.31	4.62	0.07	1.29	14.5	0.09	k_A>K	internal
	ABg	6813.3	6813.3	1	7592.8	7592.8	1	1.89	22.5	0.08	k_A, k_B >K	
	AB	2594.3	2594.3	1	2594.5	2594.5	1	3.57	17.4	0.21	k_A, k_B >K	
	$ABCg$	4235.7	4235.7	1	1108.8	1108.8	1	6982.4	6982.4	1	k_{ϕ}>K	
Line L_1 (20km away)	Ag	0.57	480.2	0.001	0.40	201.1	0.002	3.96	258.3	0.015	k_{ϕ}<K	external
	ABg	4.98	3744.3	0.001	6.05	3754.8	0.002	1.01	825.7	0.001	k_{ϕ}<K	
	AB	2.81	2145.7	0.001	3.26	2004.3	0.002	52.6	338.1	0.155	k_{ϕ}<K	
	$ABCg$	4.11	2685.5	0.001	9.09	5557.2	0.002	4.77	3573.4	0.001	k_{ϕ}<K	

VII. Biographies

DUAN Jian-dong was born in Jiangxi, China, on June 28, 1973. He obtained his BSc degree from Huazhong University of Science and Technology, China in 1995 and MSc degree from Guangxi University, China in 1998. He is now a PhD candidate in the School of Electrical Engineering, Xi’an Jiaotong University. His research interests are in power system analysis and protective relaying.

ZHANG Bao-hui (S’99) was born in Hebei, China, on August 7, 1953. He received his bachelor, master and doctor degree in the Department of Electric Engineering of Xi’an Jiaotong University in 1977, 1982 and 1988 respectively. He is now an IEEE Senior Member and a professor of Xi’an Jiaotong University. His research areas are protective relaying, transient stability and control of power system, power system communication, etc.

LUO Si-bei was born in Henan, China, on January 1, 1982. He obtained his BSc degree from Zhengzhou University, China in 2004. He is now a Master candidate in the School of Electrical Engineering, Xi’an Jiaotong University. His research interests are in power system analysis and protective relaying.