Digital Protective Relaying Algorithms for Double Circuit Lines Protection

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Abstract-- This paper presents digital relaying algorithms for double circuit lines protection using synchronized phasor measurement units. Most of the double-circuit lines in Taiwan are built in the same tower and they are generally untransposed. Therefore, this paper focuses on the design of relaying algorithms for untransposed double circuit lines. The basic principles are extended from those of a single-circuit line. The functions of the developed algorithms include fault detection, internal and external faults discrimination, and faulted-circuit identification. Both of two-terminal three voltages and six currents in the two protected circuits measured by PMUs are used in the algorithms. EMTP/ATP simulator is used to verify the performance of the proposed algorithms. Some typical responses of the algorithms are reported.

Index Terms-- Discrete Fourier Transform (DFT), double circuit lines, Phasor Measurement Unit (PMU), Global Positioning System (GPS), transmission line protection.

I. INTRODUCTION

Double circuit lines are commonly utilized in modern transmission networks but they are difficult to be protected [1]-[5]. Traditional line protection uses measured quantities at one-end of the protected-line terminal to determine if a fault occurs. For example, the distance relays are often used to protect double circuit lines. However, the problem of underreach/overreach degrades its performance due to mutual coupling effect, fault resistance, remote infeed current, etc. Some methods have been proposed for improving the distance protection performance of double lines protection [1]-[5]. These techniques are very instructive and achieve some degree of improvement for the distance protection of double lines.

With advancements of GPS and digital communication technology, the unit protection scheme using GPS for data synchronization is very attractive. For example, a GPS-based digital current differential relay is proposed and developed in

[6]. Moreover, real-time wide area synchronized phasor measurements offer new opportunities to developed advanced solutions for power system protection [6]. Many studies have verified that the protection schemes using multi-terminal data can provide better performance [7]-[9].

Since the new right-of-ways are difficult to obtain in Taiwan, many double circuit lines exist in Taiwan power system. Based on our previous research [7]-[9], we design new digital relaying algorithms for transposed/untransposed double circuit lines protection in this paper. The basic principles are described in section II. EMTP/ATP simulator is selected to evaluate the performance of the proposed relaying algorithms and some simulation results are shown in section III. Finally, conclusions are given.

II. BASIC PRINCIPLES

A. Relaying Algorithms for a single-circuit line

The authors have developed a PMU-based protection scheme using two-terminal synchronized voltage and current phasors for a transposed single-circuit line [7]-[9]. The inter-phase quantities are decoupled using Clarke transformation and then a fault detection index is given by

$$M_m = \frac{1}{2} \exp[-\Gamma_m L] [V_{sm} + Z_{cm} I_{sm}] - \frac{1}{2} [V_{rm} + Z_{cm} I_{rm}] = E_m - B_m \quad m \equiv 0, \alpha, \beta \quad (1)$$

where L is the total length of line, Γ_m represents m -mode propagation constant, Z_{cm} represents m -mode surge impedance, and V_{rm} , V_{sm} , I_{rm} , I_{sm} represent the synchronized m -mode measurements of receiving end/sending end voltages and currents, respectively.

Only using the composite index M_m , the tasks of fault detection and fault direction discrimination can be achieved [9]. The principles are described as follows:

1) Internal and External Fault Detection

The fault detection index $|M_m|$ (the absolute value of index M_m) will be held at zero under healthy conditions [7], [9]. However, the detection index will rise with a very large slope whether internal or external faults. For an internal fault, we obtain $|E_m| \neq |B_m|$ and $\angle \theta_{Em} \neq \angle \theta_{Bm}$, so that $|M_m| \neq 0$. And the index $|M_m|$ will quickly rise to a steady value. For

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external fault cases, the index $|M_m|$ will decay with time. Consider the physical measurements inaccuracies and numerical calculation errors, $|M_m|$ may not equal to zero. Therefore, a predefined threshold is needed to avoid an error action.

2) Fault Direction Discrimination

As shown in (1), the proposed fault detection index M_m is consisted of two complex phasors. Using the angle difference between these two phasors, we can attain fault direction discrimination. From the $\arg(E_m/B_m) = \arg(|E_m|\angle\theta_{Em}/|B_m|\angle\theta_{Bm}) = \angle\theta_{Em} - \angle\theta_{Bm}$, the internal and external faults can be discriminated by the following criteria [9]:

Internal fault: $\text{abs}[\arg(E_m/B_m)] = \text{abs}(\angle\theta_{Em} - \angle\theta_{Bm}) \neq 0$ (2)

External fault: $\text{abs}[\arg(E_m/B_m)] = \text{abs}(\angle\theta_{Em} - \angle\theta_{Bm}) = 0$ (3)
where $\text{abs}(\cdot)$ denotes the absolute value and $\arg(\cdot)$ denotes the phase angle.

For an internal fault case, the value of $\text{abs}[\arg(E_m/B_m)]$ rises to a certain value with a large slope. For an external fault case, the absolute value of the $\arg(E_m/B_m)$ will decay to zero quickly. Thus, from (2) and (3), we can set a threshold incorporated with a counter limit to discriminate fault zone.

B. Relaying Algorithms for Double Circuit Lines

The above relaying algorithms can be easily extended to transposed/untransposed double circuit lines. As same treatment of a single-circuit line, fully transposed double circuit lines could be also decoupled using transformation matrix in (4) and the six uncoupled single-phase modes with the same form as shown in (1) [10].

$$[T] = \frac{1}{\sqrt{6}} \begin{bmatrix} 1 & 1 & \sqrt{3} & 1 & 0 & 0 \\ 1 & 1 & \sqrt{3} & 1 & 0 & 0 \\ 1 & 1 & 0 & -2 & 0 & 0 \\ 1 & -1 & 0 & 0 & -\sqrt{3} & 1 \\ 1 & -1 & 0 & 0 & -\sqrt{3} & 1 \\ 1 & -1 & 0 & 0 & 0 & -2 \end{bmatrix} \quad (4)$$

If double circuit lines are not transposed, the coupling quantities of the untransposed double circuit lines also can be decoupled with transformations to modal parameters derived from eigenvalue/eigenvector theory [10]. However, the modal transformation matrices for untransposed lines are no longer known a priori and must be calculated for each particular pair of line parameter matrices [10]. Then, six modal fault detection indices can be also derived with the same form as (1) for untransposed lines. From above analysis, we know that the principles of the fault detection and fault direction discrimination for double circuit lines are the same as that of a single-circuit line.

Under the case of transposed double circuit lines, if the modal transformation matrix in (4) is used to decouple the phase components of measured signals into the modal

TABLE I
A LIST OF CORRECTNESS OF FAULT DETECTION INDEX M FOR DIFFERENT FAULT TYPES UNDER MODAL TRANSFORMATION

Fault Type	Circuit 1						Circuit 2					
	1	2	3	4	5	6	1	2	3	4	5	6
ag	*	*	*	*	*	*	*	*	*	*	*	*
bg	*	*	*	*	*	*	*	*	*	*	*	*
cg	*	*	*	*	*	*	*	*	*	*	*	*
absg	*	*	*	*	*	*	*	*	*	*	*	*
bcsg	*	*	*	*	*	*	*	*	*	*	*	*
csg	*	*	*	*	*	*	*	*	*	*	*	*
absg	*	*	*	*	*	*	*	*	*	*	*	*
abes	*	*	*	*	*	*	*	*	*	*	*	*
ab	*	*	*	*	*	*	*	*	*	*	*	*
bcs	*	*	*	*	*	*	*	*	*	*	*	*
cs	*	*	*	*	*	*	*	*	*	*	*	*

Letters 'a', 'b', and 'c' represent phase-a, phase-b, and phase-c, respectively.
Letters 'g' and 's' represent 'ground fault' and 'short fault', respectively.

quantities, then it will provide the modal pattern as shown in Table I. The '*' mark in the table indicates that the six modal indices, $M_i, i=1, 2, \dots, 6$, can be used to detect faults. For example, if a phase-'a' to ground fault occurs in circuit 1, then the values of mode 1~4 indices will be greater than the predefined threshold and the values of mode 5~6 indices are below the threshold. From the shown table, it is clearly seen that the available modal indices M_i in mode 3~6 with respect to circuit 1 and circuit 2 have different patterns. So, the faulted-circuit identification task for transposed lines can be easily achieved. By monitoring the values of $M_3 \sim M_6$, the faulted circuit can be easily identified.

For untransposed cases, however, it may provide six available modes when we use the decoupling matrix computed from eigenvalue/eigenvector theory. Therefore, the faulted-circuit identification task cannot directly be achieved. Fortunately, the available modal quantities are dominated by modal transformation matrix. If the transformation matrix in (4) is used to transform the phase quantities to modal quantities for untransposed lines, there will be an unknown offset value for the six fault detection indices under healthy conditions since the inter-phase quantities are not completely decoupled. Under fault conditions, however, the available modal fault detection index will deviate from the offset value with a large slope but only cause some variations for unavailable mode signals. We define a modified fault detection index as follows:

$$|\bar{M}_m| = |M_m|/|M_m|_{fd} \quad (5)$$

where $|M_m|$ is the modal fault detection index using transformation matrix in (4) and $|M_m|_{fd}$ is the value when the fault is detected.

Therefore, the value of $|\bar{M}_m|$ will deviate from 1 with a large slope for available modal signals and only cause some variation for unavailable modal signals after fault detection. At this time, the available pattern of modal quantities is the same as Table I. So, we can use the transformation matrix of (4) incorporated with a threshold setting to perform the faulted-circuit identification task for untransposed lines.

Fig. 1. The one-line diagram of the simulated transmission system.

III. PERFORMANCE EVALUATION

To verify the performance of the proposed relaying algorithms, a 345 kV, 60 Hz untransposed double circuit lines system is modeled using EMTP/ATP simulator [11] and its one-line diagram is shown in fig. 1. The phase angle difference between E_S and E_R is set as 20 degrees. The transmission line parameters are calculated by EMTP 'LINE CONSTANTS' program based on related data. T1 and T2 are the protected lines and the sampling rate is 1920 Hz (32 points per cycle). The voltage and current waveforms are filtered using second order low-pass Butterworth filters whose cutoff frequency is 300 Hz. The full-cycle DFT is utilized to estimate fundamental phasors. Three threshold settings are used in the relaying algorithms and described as follows:

- **TH1**: the fault detection level and its value is set as 2000.
- **TH2**: the internal and external fault discrimination level and it is set as 0.5 (rad). For the sake of high reliability, when four consecutive computed absolute value of $\arg(E_m/B_m)$ are greater than the predefined threshold, an internal fault is identified. Otherwise, the faults are discriminated as external faults.
- **TH3**: the threshold setting for faulted-circuit identification and its value is set as 20.

Extensive fault simulation studies are performed and some typical post-fault responses of the algorithms are reported below to show the effectiveness of the relaying schemes.

A. Relay Response for Internal Faults

Fig. 2 shows the relay responses for a phase-'a' to ground fault occurring in circuit 1. The fault resistance is 1 ohm and the fault position is set at 30 km away from bus B. From fig. 2-(a) and (b), it is seen that the fault is detected and discriminated as an internal fault at 2.083 (ms) and 4.167 (ms) after fault inception, respectively. The responses of the modified fault detection indices $|\bar{M}_m|$ for faulted-circuit identification are shown in fig. 2-(c). As shown in this figure, the algorithm correctly identifies that the circuit 1 is the faulted-circuit since the response curves of mode 5 and 6 are less than the threshold setting **TH3**. It should be noted that the value of only one modified signal of mode 3 or 4 is greater than the threshold; we could confirm that the fault occurs in circuit 1 when both of the values of mode 5 and 6

Fig. 2 The relay responses for a phase-'a' to ground fault.

are less than the threshold. For clearly explanation of the proposed fault detection and fault direction discrimination algorithms, the figures 2-(a) and (b) only depict the responses of one mode signal. In practice, there may be more than one mode signal can detect faults.

To evaluate the effect of fault resistance on the algorithms, a phase 'b'-'c' to ground fault occurring in circuit 1 is simulated and the fault resistance is set as 100 ohm. The relay responses for the internal fault are shown in fig. 3. From the figure, we observe that the proposed relaying algorithms still work very well and correctly. Since fault path resistance is completely eliminated using two-terminal measurements, the protection scheme is almost unaffected by fault resistance.

To verify the correctness of the faulted-circuit identification algorithm, a phase-'c' to ground fault occurring in circuit 2 is simulated. As shown in fig. 4-(a) and (b), the internal fault is quickly detected and identified. From the responses of the modified fault detection indices shown in fig. 4-(c), it is seen that the signals of mode 5 and 6 are greater than the threshold so the faulted-circuit is circuit 2.

From the above simulation studies, it is shown that the relaying algorithms, including fault detection, fault discrimination and faulted-circuit identification, work very well and can provide fast tripping decision for breakers.

Fig. 3 The relay responses for a phase 'b'-'c' to ground fault.

Fig. 4 The relay responses for a phase-'c' to ground fault occurring in circuit 2.

Fig. 5 The relay responses for an external fault occurring in T3.

B. Relay Response for External Faults

Fig. 5 depicts the relay response for an external fault occurring in T3. The fault type is phase-'c' to ground fault and the fault position is set at 20 (km) away from bus A. From the figure, we observe that the fault still can be detected at 1.042 (ms) after fault inception. Since the value of $\text{abs}[\text{ang}(E_m/B_m)]$ is less than the threshold level TH2, it is correctly discriminated as an external fault.

IV. CONCLUSION

New PMU-based relaying algorithms for untransposed double circuit lines are presented in this paper. The three voltage and six current signals at each line terminal are fed into the relaying algorithm so only two relays are installed for double circuit lines protection. The EMTP studies verified that the performance of the algorithms is excellent. The presented results show that internal and external faults can be quickly detected and correctly discriminated. The faulted-circuit identification algorithm also works well. With advancements of digital signal processor and communication technology, the developed PMU-based relaying algorithms are feasible for double circuit lines protection.

V. REFERENCES

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VI. BIOGRAPHIES

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