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A threshold free synchrophasor measurement based multi-terminal fault location algorithm

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ABSTRACT

A new impedance based fault location algorithm is proposed for a generic multi-terminal transmission network consisting of a main line and tapped branches with no direct measurements available at the intermediate tapping nodes. The core of the algorithm is a threshold free faulted branch search algorithm that systematically compares the multiple estimates of voltages for the tapping nodes, computed using synchrophasor measurements at the terminals. Once the faulted branch is identified, multi-terminal fault location problem is reduced into a two-terminal fault location problem to determine the exact location of fault within the branch. The proposed algorithm is simple and does not involve resource intensive mathematical operations such as matrix inversion. The proposed algorithm was implemented as a module in an in-house developed real-time synchrophasor application software program, and its performance was evaluated using a test setup consisting of a real-time simulator, an actual synchrophasor network, and a phasor data concentrator. The tests showed that the proposed algorithm is capable of correctly determining the faulted branch, except for few faults that are very close to tapping nodes. When the algorithm is used with practical synchrophasor measurements, the fault location error was within a typical tower span for most cases.

1. Introduction

Electric energy utilities are trying to improve the reliability figures of power supply. However, faults on their transmission systems pose a major challenge to achieve the desired reliability objectives. Long downtimes can be added after permanent line faults if an automatic fault location technique is not utilized. Long downtime due to permanent faults degrades the reliability figures significantly. Problem of locating faults in two-terminal transmission lines has been thoroughly investigated and solutions have been successfully implemented. A new class of fault location problem involving transmission lines having multiple taps with no electrical measurements available at the tapping points is becoming more common. Multi-terminal line fault location is much more challenging compared to two-terminal line fault location. Many of the proposed solutions for multi-terminal fault location require use of synchronized measurements at the line terminals. Phasor measurement units (PMUs) are becoming widely available in power systems [1]. Therefore, utilization of synchrophasor measurements is a viable option for multi-terminal fault location. Since synchrophasor measurement function is available in modern relays, recorders and meters as an integral function, synchrophasor based fault location is likely to be a lower cost option when compared with transient based fault location solutions such as the method proposed in [2]. Low cost PMU designs such as [3] could make fault location feasible even at sub-transmission or distribution systems.

Most of the multi-terminal fault location techniques are derived using tools developed for two-terminal fault location or by extending two-terminal fault locations algorithms. The algorithm in [4] is one of the earliest two-terminal fault location algorithms, and utilizes transformed voltage and currents phasors applied to distributed transmission line model equations. This algorithm can be applied to locate faults in transposed or non-transposed transmission lines, and it is independent from the source impedance and fault resistance. Some attempts to solve limitations in the measurements or challenging situations are presented in literature. Two-terminal fault location using unsynchronized two-end phasor measurements is achieved in [5] by iteratively solving the voltage magnitude equation developed in [4]. To obtain more accurate fault location results for two-terminal transmission system under dynamic conditions such as power oscillations, an iterative solution is proposed in [6]. An initial fault location estimation is obtained from the steady state equations, and then nonlinear differential equations of the transmission lines are iteratively solved to obtain an accurate fault location. In [7], to alleviate influence of CT saturation on the accuracy of fault location, an equation for fault location has been developed using

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Nomenclature

N	number of tapping nodes
n	index of transmission line connected to tapping node n
K_n	number of terminals connected to the tapping node n
k_n	index of terminals which connected to the tapping node n
$\gamma_{k_n,n}$	propagation constant of the transmission line connected between the tapping node n and terminal k_n
$Z_{c_{k_n,n}}$	characteristic impedance of the transmission line connected between the tapping node n and the terminal k_n
$l_{k_n,n}$	length of the transmission line connected between the tapping node n and the terminal k_n
V_{k_n}	positive-sequence voltage measurements at the terminal k_n
$I_{k_n,n}$	positive-sequence current measurements at the terminal k_n
$\overline{V}_n^{(k_n)}$	estimated positive-sequence voltage for the tapping node n using the measurements at the terminal k_n
$\overline{V}_{n^*}^{(n^*-1)}$	estimated positive-sequence voltage for the tapping node $n*$ with the estimated voltage node for n∗-1
$\overline{I}_{k_n,n}^{(k_n)}$	estimated positive-sequence current injected from the node n using the measurements at k_n
D_n	a sub-domain of the system includes a set of branches connected to tapping node
P_F	a pointer tracks the current tapping node is being considered in forward search process
P_B	a pointer tracks the current tapping node is being considered in backward search process
P_D	a flag tracking direction of movement of the last pointers in last search
MVD_n	maximum positive-sequence voltage deviation of the estimated voltages for tapping node n
$VD_{n^*}^{(k_{n*})}$	voltage deviation between the correct node voltage estimation for n∗ calculated using adjacent node voltage and the voltage estimations using measurements at k_n*
$\hat{x}$	normalized fault distance from the sending of the transmission line

only synchronized voltage measurements. Current values are eliminated by simplifying three-phase KVL equations applied for steady state. Two indices that are evaluated using Clark transformed components of synchronized voltages and currents are proposed to detect and locate the fault in [8] and its implementation is detailed in [9].

Three-terminal fault location is a special sub-class of multi-terminal fault location. Three-terminal fault location has been investigated in [10] by reducing three-terminal fault location into a two-terminal fault location problem. A three-terminal fault location method that can be implemented in three-terminal current differential relay is described in [11]. As the current phasors measured at all three terminals are available in a current differential relay, there will be no additional cost for implementing this algorithm. An index calculated using two-terminal superimposed voltage and current synchronized phasors is proposed in [12] for faulted leg identification in a three-terminal transmission system. To locate faults in the legs directly connected to the two-terminals having measurements, the two-terminal fault location equation proposed in [8] is used with the estimated voltage and current injection at the tap point. Faults in the leg with no measurements are located with a single-terminal fault location technique with the help of the estimated pre-fault internal voltage of the equivalent source connected to the inaccessible measurement terminal. Fault location equation in [8] has been applied for three-terminal multi-section non-homogeneous transmission lines in [13]. In [14], the faulty leg in a

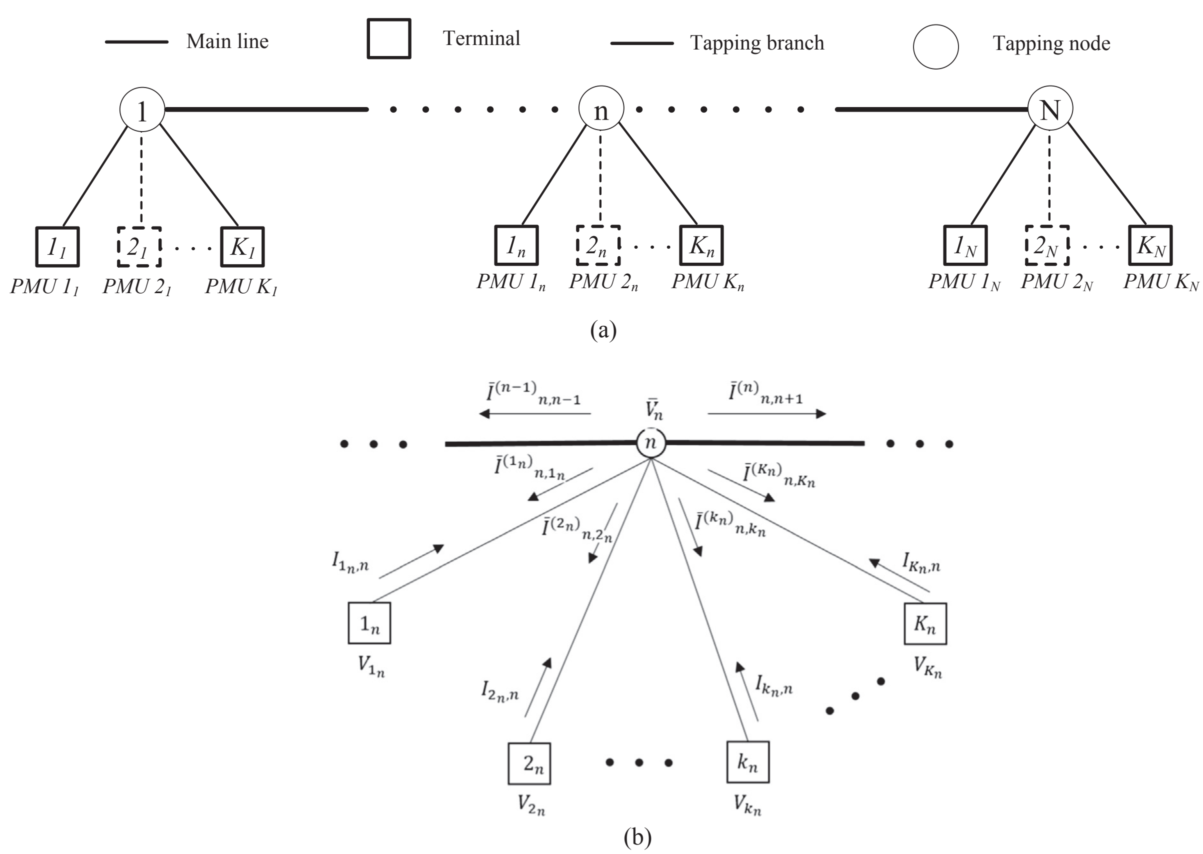

Fig. 1. Multi-terminal system. a. Structure of a multi-terminal transmission line. b. Notation used to represent branch currents and node voltages.