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Optimal multiplier load flow method using concavity theory

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ABSTRACT

This paper utilises concavity properties in the optimal multiplier load flow method (OMLFM) to find the most suitable low voltage solution (LVS) for the systems having multiple LVS at the maximum loading point. In the previous method, the calculation of the optimal multiplier is based on only one remaining low voltage solution at the vicinity of voltage collapse point. However, this does not provide the best convergence for multi-low voltage solutions at the maximum loading point. Therefore, in this paper, concavity properties of the cost function in OMLFM are presented as the indicator to find the most suitable optimal multiplier in order to determine the most suitable low voltage solutions at the maximum loading point. The proposed method uses polar coordinate system instead of the rectangular coordinate system, which simplifies the task further and by keeping PV type buses. The polar coordinate in this method is based on the second order load flow equation in order to reduce the calculation time. The proposed method has been validated by the results obtained from the tests on the IEEE 57, 118 and 300-bus systems for well-conditioned systems and at the maximum loading point.

1. Introduction

Load flow analysis is important in providing the initial conditions for many power system analyses such as transient stability, fault analyses and contingency analysis. Load flow analysis is used intensively in the planning of a new power system network or expansion of an existing power system network. In the past, a large number of solution methods have been introduced to improve various power flow problems, especially to improve the convergence speed for well-conditioned power system [1–4]. For ill-conditioned systems, researchers are more concerned on the divergence of power flow equations in conventional methods and systems operating in infeasible zone [5–7]. A power system becomes ill-conditioned due to the high R/X ratio of transmission lines or the loading of the system is approaching the maximum loading point (MLP). The stability of a power system is greatly affected in ill-conditioned system [8–10].

In load flow analysis, the load flow equations consist of an algebraic set of nonlinear quadratic equations, which have several solutions. However, at least one of the solutions is the operating point of interest for the system, which corresponds to stable equilibrium points for well-conditioned systems [1,11,12]. The load flow solutions are commonly found using the standard Newton–Raphson load flow (SNRLF) method [13,14], where flat initial guesses are made (all bus voltages of PQ-type bus equal to 1 and their voltage angles equal to zero). Although the solutions using the SNRLF method exist, stable equilibrium solutions may not be found. This is due to the region of the solutions is far from the operation point and due to the application of numerical method in the SNRLF method [12,14–16].

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Nomenclature

D	vector of independent variables
L	vector of dependent variables
S	vector function of load flow
ω	coefficient related to dependent and independent variables
G	function of nonlinear inequality constraints
W	function of nonlinear equality constraints
U	control parameter for independent variables
λ	convergence correction multiplier (optimal multiplier)
MLFS	multiple load flow solutions
HVS	high voltage solution
OEF	optimisation energy function
EFPS	energy function of a power system
MLP	maximum loading point
SNRLF	standard Newton–Raphson load flow
OMLFM	optimal multiplier load flow method

For power systems which several solutions exist, the solutions can be divided into two types; low voltage solutions (LVS) and high voltage solutions (HVS). LVS is referred to unstable equilibriums, which present a low-voltage profile in some buses while the operating point of interest is referred as HVS [16]. The number of LVS decreases when the load of the system is increased in a way that at the voltage collapse point neighbourhood, only one LVS remains. When the load of the system is increased further, the HVS can intersect with the one remaining LVS [12,17]. This LVS is called as the critical LVS in a saddle-node bifurcation point and it disappears when the load is kept increasing, where the load flow solutions become unavailable [18,19]. The load that corresponds to this critical LVS is known as the maximum loading point (MLP) [16].

There are two main approaches of finding the LVS; the curve tracing method (CTM) or path following method [8,19,20] and the state space search method (SSSM) [13,21,22]. The CTM uses a trajectory of the load increase direction to detect the MLP. This method is considered robust and powerful in detecting LVS. However, the disadvantage of CTM is for convergence, it needs a large number of iterations and previous information of the direction of the load demand increment. However, the determination of LVS using SSSM does not require many iterations and any previous information of the load increase direction. The SSSM searches for LVS in a chosen direction of the state space and then, the LVS is determined using an interactive load flow solver method [6,23].

The work in this paper focuses on ill-conditioned power flow problems. For ill-conditioned power systems, the multiple load flow solutions can be determined using the optimal multiplier load flow method (OMLFM) [13]. This method applies the optimal multiplier based on SSSM concept to the SNRLF method. It was found that the solution never diverges but converges in a way that the value of the cost function always reduces. This cost function is known as the energy function of power system (EFPS) and its derivative function with respect to the accelerator multiplier is called the optimisation energy function (OEF) [13,21]. When there are more than one real solutions of the optimal multiplier, the lowest optimal multiplier is selected, which is commonly used in most of the literature [17,24]. The optimal multiplier is then used to update the estimation of bus voltage vectors.

The optimal multiplier concept has also been utilised to estimate multiple load flow solutions by using three optimal multipliers in [21]. This method was used to find a pair of multiple load flow solutions that are closely located to each other, which is related with voltage instabilities in power systems. It was discovered that the convergent characteristics of load flow calculation by the SNRLF method in rectangular coordinates has a unique linearity. They tend to converge straight toward a pair of multiple solutions when they are closely located to each other. Therefore, Iba et al. has proposed a new method for solving a pair of near solutions in power systems. The proposed method was able to obtain those solutions by one or two times of conventional load flow calculations with additional processes. The proposed method can also confirm the existence of other solutions near a conventional solution.

Overbye in his publication has shown that the optimal multiplier from the OMLFM approaches zero at the maximum loading point due to the singularity of Jacobian matrix [15]. To overcome this problem, Overbye has selected the optimal multiplier closest to one, or the maximum optimal multiplier to find the LVS in a feasible boundary zone of the system operating point. This selection is based on the remaining LVS at the vicinity of the voltage collapse point neighbourhood. When the load is increased further, the smallest and largest roots of OEF move towards each other and meet at the local maximum point, which is at the middle root of the EFPS [14,23]. This case is referred to the system having multiple LVS at the MLP [16]. However, the direction of OEF roots movement may lead the OMLFM to blind search in detecting the LVS. This has resulted in there is no guarantee that using the optimal multiplier closest to one leads to an optimum point of EFPS [16,21,25].