Voltage stability analysis using generic dynamic load models

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Abstract— **High levels of penetration of distributed generation and aggressive reactive power compensation with modern power electronics may result in the reversal of active and reactive power flows in future distribution grids. The voltage stability of these operating conditions may be very different from the more traditional power consumption regime. We study the stability characteristics of distribution networks with reversed power flow. After introducing a universal algebraic approach to characterize all the solutions of the power flow equations, we show that new solutions appear in the reversed power flow regime even in the simplest three bus systems. We show that the some of these solutions are stable and the system may exhibit a phenomenon of multistability, where multiple stable equilibrium co-exist at the given set of parameters, and the system may converge to an undesirable equilibrium after a disturbance**.

Keywords— **Voltage stability, multistability, power reversal, dynamic load modeling, distributed generation.**

I. Introduction

The increasing levels of penetration of distributed generators, either renewable or gas-fired will cause the distribution grids to operate in unconventional conditions. The flow of active or reactive power may become reversed in certain realistic situations such as sunny weekday time in residential areas with high penetration of photovoltaic panels. Active participation of future distribution level power electronics in reactive power compensation may also lead to the local reversal of reactive power flows. These kind of operating conditions are not common to existing power grids, but may become more common in the future and may also have a serious effect on the overall voltage stability of the system. The strong nonlinearities present in the power system determine the existence, multiplicity, and stability of the viable operating points. However, most of the works focusing on multiplicity of solutions and their properties have targeted the transmission grids. There was little effort in understanding the solution manifold of distribution grids because vast majority of these networks operate in the conditions when only two solutions coexists for a given set of parameters. The structure of the manifold is very well captured by the textbook two-bus system used to describe the well-known nose-curve. The structure of the solution manifold in distribution grids in reversed power flow regime is however poorly understood, although there are reasons to believe that it will be very different from the classical nose-curve type manifold. Although the direction of the power flow does not affect the qualitative properties of the solutions in linear approximation, it becomes important when the nonlinearity is strong. The symmetry between the normal and reversed power flow solutions is broken because the losses that are the major cause of nonlinearity in the power flow equations are always positive. In traditional distribution grids the consumption of power and the losses have the same sign, while in the situation with reversed flows the processes of power injection and thermal losses are competing with each other. This competition may manifest itself in the appearance of new solutions of power flow equations that do not exist in the non-reversed power flow regime. From power engineering perspective this phenomena can be understood with the following argument. In the presence of power flow reversal the voltage is supported to be high enough for low voltage solutions to appear. In this work we attempt to address this problem by introducing a new form of the load models that is consistent with existing models in normal conditions but does not suffer from the convergence problems in abnormal situations. The paper is organized as follows.

II. POWER FLOW SOLUTION

Traditional approaches for analysis of power flow solutions based on iterative methods like Newton-Raphson, continuation power flow, and their variations [7] are not suitable for identification of all branches of the solution manifold. By construction these methods find only one solution for given set of parameters. There is no systematic way of adjusting the initial conditions that would guarantee that all solutions branches are found. Several techniques have been introduced in the literature for identification of all power flow solutions, the optimal multiplier based method, and more recently a holomorphic embedding method. An alternative approach proposed in this manuscript is based on the Grobner basis technique applicable to any systems of polynomial equations. The introduction to the Grobner basis approach can be found in, while here we introduce the well-known Buchberger's algorithm for solving the set of polynomial equations. To our knowledge this techniques has been applied to power flow equation only in but has not received wide adoption in the community.

III. DYNAMIC LOAD MODEL

The stability of the different solution branches depends on the dynamical behavior of loads on individual buses. Load modeling is a mature field that has been developed for several decades . Traditional models of load dynamics are

based on combination of differential and algebraic equations for the load state: The algebraic equations in those systems describe the so-called constraint manifold and represent the equilibrium manifold of fast degrees of freedom that relax to equilibrium on time scales below the model resolution. Typically the fast degrees of freedom describe the instantaneous response of the network to the changing loading conditions. In most of the reported models describing the slow dynamics of the system on the tens of seconds-minutes timescales, the instantaneous response of the network is modelled via nonlinear load-flow equations similar to (1). The state of the loads in those models is described by the values of active and reactive power consumption that change according to some dynamic law. Although these models are actively used in the community and have been validated in wide range of normal operating conditions, they are not always applicable
to abnormal situations when the solution of algebraic power flow equations does not exist. Similarly, this model can be ill defined in a situation when power flow equations have multiple solutions. These problems are purely mathematical and arise when the implicit modeling assumptions about the dynamics of fast and slow degrees of freedom no longer hold. In order to overcome these problems we introduce an alternative representation of load models that is equivalent to the standard models in normal operating conditions but does not suffer from convergence problems in abnormal situations.

IV. DYNAMIC SIMULATIONS OF A THREE THREE-BUS NETWORK

In this and the second sections, we perform dynamic simulations of two simple networks to show that two stable equilibrium of load dynamic equations may coexist at the same time, and that the distribution system may become entrapped at the lower voltage equilibrium. First, we consider a three-bus network as shown in Figure 1 with bus 1 being the slack bus and buses 2 and 3 representing the dynamic loads with distributed generation exporting reactive power. This system could represent the future distribution grids with the inverters of PVs panels participating in voltage regulation .Alternatively, it could represent highly capacitive grid, for example involving long underground cables. be an important problem for the future grids. The good candidates for the actuators of these control loops are ULTCs or responsive loads.

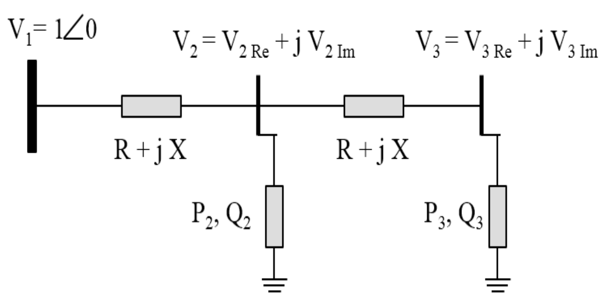

Fig. 1: A three-bus network

V. POWER REVERSAL REGULATIONS

To prevent the entrapment of the system at the lower branch of the nose curve, new policies for power reversal need to introduced. The stability of the system depends both on the active and reactive power dynamics and has to be accounted for in the regulations. Standardization based on power factor may not guarantee the stability of higher voltage branches. The existing standards for DG penetration may not be adequately assessing the voltage reliability and security of the system. Unlike transmission grids, the distribution systems are usually operated without designated distribution system operator monitoring the state of the grid and usually rely on the fully automated control. This situation is unlikely to change in the nearest future, and poses a risk for future system with high levels of DG penetration where the power flow reversal is possible.

VI. SIMULATION RESULTS

The bus 3 has base demand level Ps3 = −0.75 p.u., Qs3 = −0.45 p.u. which corresponds to a capacitive load producing active power.

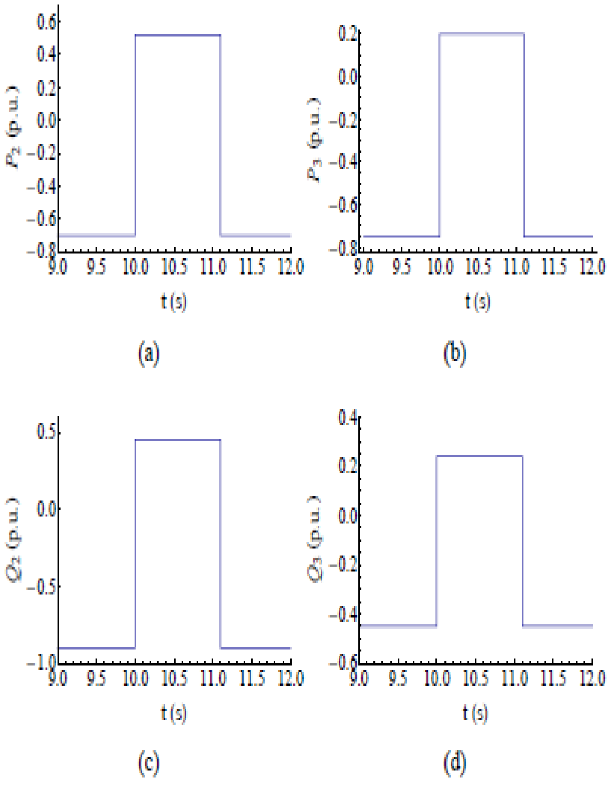

Fig. 2. The power demands at bus 2 and bus 3 during the first disturbance

After the system reaches the high voltage equilibrium, a large disturbance occurs, i.e. distributed generation partly is lost. For example it could represent the cloud covering the PV panels with a shadow. Therefore, the loads change their modes from generating to consuming both active and reactive powers as in Figure 2.

A suggested initial condition is g2 = −0.324 p.u., b2 = −0.416 p.u., g3 = −0.269 p.u., b3 = −0.161 p.u. The transient of the system is shown in Figure 3 following the blue arrows.

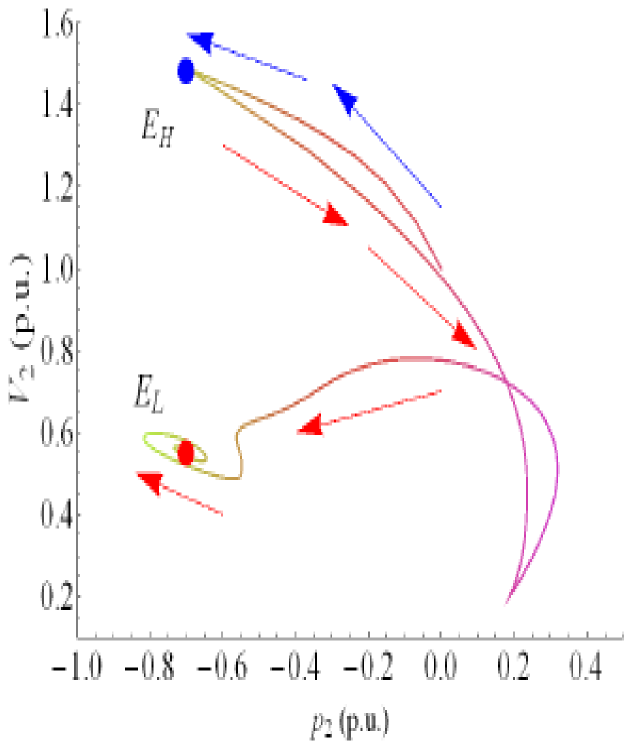

Fig. 3. The PV curve at bus 2, t < 20 s

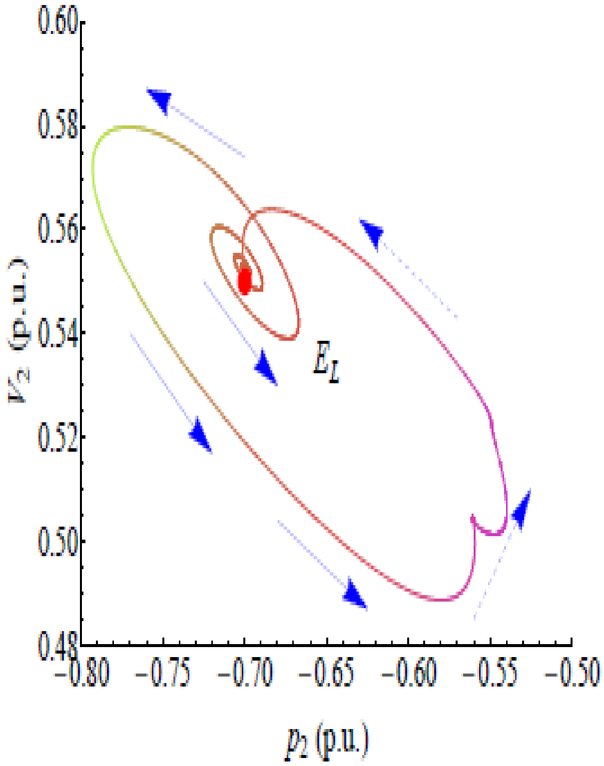

Fig. 4. The PV curve at bus 2, 20 s < t < 30 s

At td = 20 s the second disturbance in Ps2 occurs that changes the demand Ps2 to some lower value Ps2 = −0.56 p.u. for 2 s. As shown in Figure 4, the system first moves away from the low voltage equilibrium following the blue arrows then returns back to the same equilibrium following the blue dashed arrows.

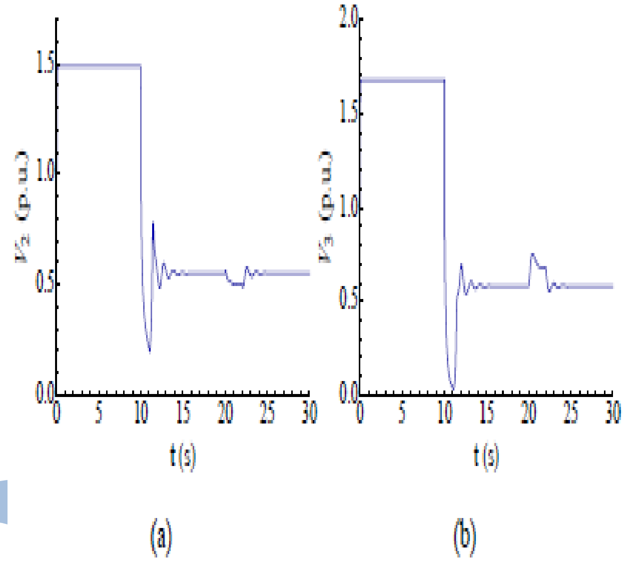

Fig. 5. Voltages at bus 2 and bus 3 for the small second disturbance, t < 30.

Figure 5 shows how the voltage at bus 2 and bus 3 illustrates changes between two voltage levels.

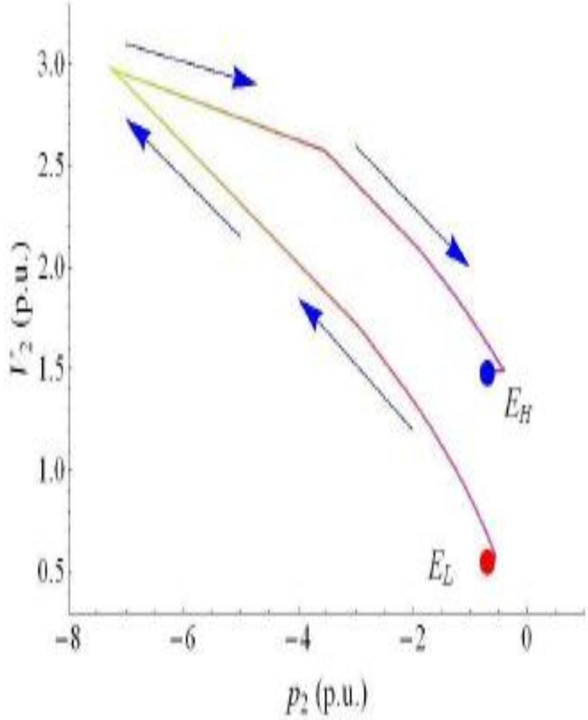

Fig. 6. The PV curve at bus 2, 20 s < t < 30 s

The similar disturbance can happen when PVs generation reduces. Consequently, the system returns to the high voltage equilibrium with the trajectory shown in Figure 6.

VI. CONCLUSION

In this work we have shown that distribution grids with active or reactive power flow reversal can have multiple stable solutions of the power flow problems. We proposed a novel technique for characterization of all the solution branches based on the Grobner basis approach. The stability of the low voltage solution branches has been demonstrated with the dynamic simulations based on the new representation of the standard load models that does not suffer from the divergence problems. More analysis is required to establish new regulations that prevent the entrapment in future power grids with high penetration of DG and power electronics. In the future works we plan to extend the Grobner basis approach to large systems with the help of reduction and approximation techniques. The extension of this approach could be useful for development of nonlinear dynamic equivalents of large-scale distribution grids and the effects of distributed controls on the overall system stability. Incorporation of dynamic stability analysis in the planning stage decision making process may require new stability criteria that guarantee the stability in the presence of load uncertainty.

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