Employing the Pre-Existing Direct Methods and New Techniques in Analyzing Stability of Power System

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***Abstract*: The Department of Energy has set necessities by 2030 to utilize renewable resources that don't deliver hurtful results, similar to CO2, coal fiery debris and atomic waste. While different wellsprings of renewable energy resources can be more productive, sun based energy can be ideal to use in specific areas when the measure of sun radiation is high and the cost of land is moderately cheap. One of the approaches to change over sun powered radiation into electricity is utilizing Photovoltaic (PV) cells. PV cells can change over sunlight based radiation into DC electricity, which at that point is changed over to AC through inverters previously incorporating it to the lattice. Inferable from the EPA directions, utilities are headed to intensely diminish their carbon impressions. On account of Dominion VA Power, this drive is additionally energized by a 30% duty credit for sun oriented designers. In this manner, a ton of dissemination and transmission interconnected PV is normal. To get the most extreme monetary advantages, it appears to be appealing to dislodge the more costly traditional cresting units. While being a monetarily and also naturally reasonable alternative, this has prompted genuine phenomenal unwavering quality worries because of vulnerability in sun oriented yield combined with the idea of this sort of generation. Right now PV isn't thought of as a help for the lattice attributable to its yield vulnerabilities. While being an inverter based generation gives huge flexibility in controlling, it comes at an additional cost.**

***Keywords*: DC electricity, Photovoltaic, EPA directions, VA Power, electric load, power generation**

1. Introduction

The regulation and monitoring of voltages were more and more complicated to schedule and run, especially in longitudinal networks, over the last few years. To order to satisfy the growing demand for energy, companies tend to focus instead of constructing new transmission lines on the current generation and production exports and import agreements. The need to optimize the usage of current transmission networks has been expressed in this. At the other side, the energy flows are far below their thermal limits in some transmission lines, while some lines are overloading which typically decreases the voltage profile efficiency and the reliability and protection of the network. However, in most situations, current conventional transmission networks do not fulfill the control criteria of advanced dynamically integrated power systems.

1.1 Voltage Stability

"Throughout the operation and preparation of the power grid, assurance of steady state voltage stability is critical. The primary factors pushing the utilities to run their grid closer to the power distribution efficiency mark are deregulated regulations, environmental regulation, construction costs of modern transmission lines and increased rise in demand. As a consequence, there is an growing chance of voltage instability or voltage drop. This is evident from many accidents concerning the loss in voltage worldwide. For the functioning of the device with adequate safety margin, it is therefore important to evaluate the voltage stability maximum under different operating conditions. The key source of volatility is the control system 's failure to fulfill efficient capacity specifications. Two solutions to the static and dynamic stabilization of voltage are commonly valid. The study of stability of static voltage is based on a traditional or updated power flow equation solution. This provides the opportunity to meet a particular load requirement from the transmitter network. The theoretical solution tries on the other side to evaluate when and how the voltage plummeted. Numerous approaches for evaluating the static stability maximum are already suggested in the literature. There is a P-V and Q-V graph, multiple solution for load flows, power flow solution for continuity, a fixed value of one's own, energy-based response and fork approaches."

"Researchers have recently tried a quick method that is suitable for online applications. Both strategies require significant time and measurement measures, since this relies on the option of control stage frequency. Evolutionary approaches have been implemented lately to address problems of voltage stability, such as genetic algorithm (GA) , particle swarm optimization, and hybrid particle swarm optimization."

1.2 Importance of voltage stability

Maintaining sufficient voltage has become an significant issue because many utilities are pushing out as much of the mass transmission network as possible to avoid capital costs in the building of new lines and generation facilities. The need to retain adequate sensitive margin for such device situations does not become simple to handle as the bulk transmission network is forced beyond its thermal capability. In comparison to true strength, the MVAR reserve margin can be very difficult to correctly measure. The fact that VARS flows to help voltage of the bulk transmission network renders the issue more complex. Under high load settings, the applied reactive power cannot be adequate to decrease the voltages. In certain situations, the voltage drops triggered by falling a generator or a transmission line cannot be recovered for heavily charged power systems , especially where the network design involves long transmission lines, even though the static condensers are turned off at the load ends. It is what is known as voltage instability or voltage decline phenomenon. The level of incidence has contributed to work in a different direction in the reliability study of the power supply network."

"Presently, many power systems worldwide are undergoing voltage related problems for more than one reason. A more systematic approach to voltage phenomena is currently needed since new operational strategies directly affecting the system voltage profile are taking place. This situation calls for exploring the potential of voltage control measures that are made more flexible to react to changing system conditions. A good voltage profile is important for three reasons:"

- Better security
- Good quality of supply
- Low transmission loss

"Therefore, under all operational conditions bus voltages in a narrow band must be held about the stated value. This is one of the biggest operational problems recognized. Both power systems have a certain percentage of reactive power reserves that are of the right sum and this can help to create a stronger voltage profile at the required time."

"When the systematic modeling and solution of the operational power framework are quite difficult, theoretical research is not straightforward. Most utilities in the Energy Management Systems monitor system voltage profile. The human operator uses this knowledge to determine whether to establish reference points at different voltage control points or to turn the sensitive power carrier. There are multiple goals to be achieved for any given large utility. Security, economic function and stability in a power network are the usual targets. It could be clear, because of its particular existence, that the balance between such objectives is unlikely. In other terms, the different goals can not be handled in the same way. Operators have used expertise and on-the-ground network environments to ensure stable efficiency. Power networks are more complicated today, though. A large number of potential scenarios that trigger problems outside the analytical capabilities of the operator. Therefore, most utilities use computer-aided dispatch to help the operator monitor the system, manage economic dispatch and assess voltage stability."

1.3 Transient Stability of Power Systems

Transient steadiness is characterized as the capacity of a system to come back to the harmony following an extreme unsettling influence, for example, flaws, loss of generation, and so forth. The wonder is set apart by huge outings in generator rotor points, voltages, and so forth requiring non-direct models to recreate and think about. This sort of flimsiness is typically clear inside couple of moments of the aggravation. Before plunging further into the possibility of transient solidness, we would first give the peruser a general foundation on the electromechanical elements (swing equation) that go ahead inside a synchronous machine amid these aggravations. This will be trailed by an understanding into the marvel of how a multi machine system normally loses strength. This area is gotten from.

1.4. Swing Equation

A synchronous machine (customary generators) is contained a round and hollow rotor secured by curls conveying DC current, turning to make an attractive field pivoting in space with a similar speed in space. These turning attractive field lines cut the spatially conveyed windings on the settled segment of the generator (called the stator) to prompt an electrical potential in them (through Faraday's law). This potential is AC write with a precise recurrence (ωe) identified with the recurrence of rotor's mechanical speed (ωm) having P attractive shafts on the rotor as

$$\omega_m = \frac{2}{P} \times \omega_e$$

1.5 Power-Angle Relationship and Stability Phenomenon

In this segment we talk about the connection between the exchange power and precise position of the rotor of synchronous machines which is imperative trademark overseeing power system stability. The power trade in a two machine system given beneath with machine 1 (generator) bolstering machine 2 (engine) is of the frame –

$$P = \frac{E_G E_M \sin(\delta)}{X_G + X_L + X_M} = P_{max}\sin(\delta)$$

Multi-machine System Network Reduced Model

The general power system show comprises of transports (nodes) between associated through transmission lines. These transports have gadgets connected to them (say for effortlessness generators with its controls and loads). Burdens can go from basic static ones like consistent power utilization to complex unique ones like enlistment engines. The generator and its controls (AVR, governor, PSS) can have exceptionally refined complex models.

Transient Stability during Power System Faults (Concept of Critical Clearing Time)

The most extreme kinds of unsettling influences with regards to keeping up transient stability are transmission organize shortcomings. These allude to circumstances when one more periods of a transmission line get accidentally associated with each other or to the ground or both. This sort of an occasion is typically set apart by hazardously low voltages and high streams in the system. The system typically does not have a tasteful harmony as long as the blame maintains. Along these lines, these need to 13 be cleared which is generally done by transfers which separate the blamed locale (line, generator, and so forth) of the system.

In view of our exchange, a portion of the components that obviously affect transient stability are –

a) Generator parameters ($M\&D$). Lower the estimation of these parameters more is the speed picked up amid unsettling influence.
b) Base stacking on the generator ($Pm0$). Higher the $Pm0$, more is the quickening (for a similar measure of power confuse), more is the speed picked up and more changes of δ achieves flimsy esteem.

c) Terminal voltage E. Lower the E, lesser the effect of Pe for same increment in δ after the blame is cleared. We can see that when δ increments, Pe increments and turns out to be more than Pm which is the main power that contradicts the generator which has picked up speed amid blame.

d) Post blame system impedances. Lower the impedance esteem, higher is the power point bend and in this way bring down is the plot for same measure of yield power

2. Utilization of Direct Methods For Inverter Protection

Traditionally, the inverter based generators were made to trip offline during major disturbances as they were not treated like regular generation for grid support. Since large amounts of PV are being incorporated into the grids all over the world, this translates into large amounts of generation lost during disturbances. This poses a serious threat of system collapse. Inverter ride through capabilities safeguard against these scenarios. The ride through standards defines operating requirements for PV to not trip offline. These are primarily arrived at keeping the protection of inverter as well as utility preferences in mind. However, these generators still are tripped offline due to various reasons. Firstly, the fault current contribution of these generators is determined by the solar irradiance and current limiter logic unlike conventional generators which can provide extremely high fault currents. Thus, effectively, the internal impedance of the solar PV generator changes a lot throughout the day. Specifically for distribution systems, the protection system is overcurrent based which makes it challenging to design for distribution connected PV systems. Therefore, these need to be deliberately tripped offline during nearby faults in order to stop feeding the fault from the point of view of safety of the personnel. Also, utilities do not have total control over most of these generators because they are mainly privately owned. As for the larger sites, they are a mix of utility owned and privately owned with full control over the former type but these still need to follow the NERC standards for ride through characteristics. There is also a level of uncertainty associated with this type of generation which further puts a doubt over dependability and therefore another reason why the utilities trip them offline during major events. However, the ride through standards for both transmission and distribution connected PV are still under development and not fully adopted yet by inverter manufacturers adding more complexity to the system. These standards are mainly voltage and frequency ride through curves which define the time dependent operating limits (upper and lower) on voltage and frequency respectively at the point of interconnection to the grid. Power system faults which result in depressed voltages constitute the major portion of the events that threaten the transient stability and therefore will be the focus of our studies. The low voltage ride through (LVRT) curves defined for each inverter which as the name suggests give a lower limit on the voltage as a function of time are the main culprits for tripping PVs during these events. For the remainder of this thesis, we will be treating the tripping of the PV synonymous to its lower voltage limit (from LVRT curve) violated. However, the techniques that will be developed can be easily extended to incorporate other ride through constraints as well. The standard ride through curves vary a lot and are carefully designed based on the characteristics of the grid they are deployed in. For example, a system with a lot of induction motor loads is known to have a much slower voltage recovery than systems with static loads. So, voltage recovering to nominal values in 5 minutes might be normal for the former cases while abnormal for latter. Shown below are LVRT curves defined by various standards. As we can see that these can be quite different from each other.

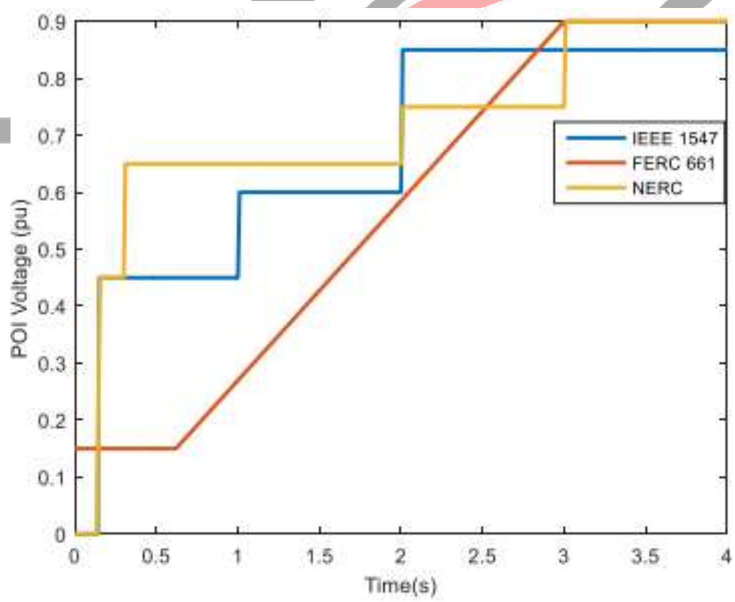

Figure 1 LVRT Standards

Thus, with increasing renewable penetration, we will have power systems relying on generation which is made more prone to trip offline. This added complexity makes the problem of studying power system transient stability using direct methods much more complicated. To the best of our knowledge, this problem has not been tackled in its entirety and thus we plan on taking the first steps. In this chapter, multiple approaches will be proposed differing in the way this uncertainty is handled. We will be majorly relying on SOS programming by demonstrating its effectiveness in dealing with complex systems such as this. It should be kept in mind that in this section of work, the power system model in single machine reference frame (with n_g^{th} machine as the reference) is used as opposed to COA frame in the previous section. Also, PV will be modeled as a negative real load in accordance with the common modeling practices. Thus, the inverter dynamics are totally ignored with no reactive support from them.

3. Approach of Constrained System

Traditionally, the aim of transient stability assessment used to be to capture the mode that resulted in loss of synchronism of synchronous machines. This was characterized by the post disturbance system trajectory leaving the SR of the corresponding SEP as discussed before. However, another potentially severe scenario that has emerged in systems with prone to tripping renewable generation is a single generation tripping event triggering a cascading sequence. Since the PV location is heavily dependent on the land prices, it is common to see multiple PVs connected in the same region of the grid. This makes increases the chances of cascaded tripping which could potentially lead to system collapse. Thus, in this section, we treat tripping of even a single PV as an instability phenomenon.

Let us now give a brief background in the type of systems we will be dealing with called the constrained systems. There are mainly two types of commonly present constraints in dynamical systems viz. equality and inequality constraints. Equality constraints when present, force the systems to evolve over a manifold. Thus, if we restrict the starting point of a trajectory to the given constraint manifold, the emerging trajectory will always stay on it. An example is the power system which is constrained to satisfy a balance in nodal injections (Kirchoff's laws). The inequality constraints usually stem from the physical limitations of the system or system designer's preferences. Since we are only focusing on the LVRT, the inequality constraint in our case requires is that the voltage at each PV's point of interconnection should be above the respective LVRT curve. Due to the presence of these inequality constraints, the state space is divided into feasible and infeasible regions. In our problem, the former consists of all those points that do not violate the ride through constraints of any of the connected PVs in the system. Unlike the equality constraints, the inequality constraints do not influence the system dynamics. What this means is that the system will behave as though it did not have any inequality constraints.

From the point of view of stability, an added characteristic of a stable trajectory is that it should not enter the infeasible region. This requires us to define a CSR vs an SR for the desired SEP. Here the word constrained represents only inequality constraints. This could be thought of as the largest invariant portion of the corresponding unconstrained system's SR that does not intersect the infeasible region. It is important to keep in mind that CSR is smaller than unconstrained SR minus the infeasible region which can be understood from the following figure. The ellipse represents the SR of the unconstrained system for the SEP. everything lying above the feasibility boundary is infeasible while below it is feasible. Now, one big requirement for the CSR is that it should be invariant. This is because we want the trajectories to always remain in the feasible region as well as the SR (which ensures they converge to). In this case, we can clearly see that the region defined by unconstrained SR minus the infeasible portion (upper sector) is not invariant. This is because the trajectory starting from the marked test point which is still inside the feasible region and SR breaches the feasibility boundary thus not a part of the CSR (shaded grey area).

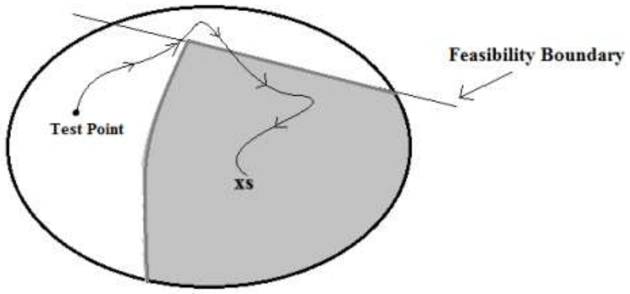

Figure Constrained Stability Region (Grey)

4. Conclusion and future work

Switching sequence independent of the time between switchings was proposed using Lyapunov's direct method and SOS. We then started by addressing a more general problem of assessing the impact of cascading tripping of PVs on stability. The risk of instability region was defined which coupled the chances of cascading tripping based on historical data with the SR estimates for each cascading sequence. While still in the conceptual phase, this idea has potential applications in helping the system planner identify the cascading scenarios to be stopped by strategizing the blocking of certain PVs from tripping to save the system from potential collapse. This was followed by a methodology for the transient stability assessment of systems with trippable PV which used a different CSR for each range of fault clearing time. While the proposed technique had inherent conservativeness resulting from the Lyapunov approach as well as the LVRT curve approximations, nevertheless it provided a reliable estimate of system stability for such systems.

The motivation behind this work was to modify and develop direct methods for transient stability assessment of power systems with added complexities resulting from increasing PV penetration. That being said, there are a lot of questions still left unanswered which opens several topics for future research –

- Impact of uncertainties in PV outputs: One of the major issues with operating a grid with a large penetration of PV or other renewable generators is the associated uncertainties in the output. This results in a system with multiple possible operating conditions which requires the stability assessment of each. A direction of research could be in exploring the potential of SOS programming in dealing with parameter uncertainties. Also, exploring sampling methods in order to reduce the number of operating conditions analyzed individually using any of the direct methods.

- Analyzing the influence of detailed inverter models: PV was modelled as a constant real power injection thus ignoring the inverter side dynamics as well as grid support capabilities in our studies. With the increasing penetration of these generators, the inverter dynamics are expected to play a major role in the system behavior thus requiring further assessment. Also, the inverter grid support capabilities in the form of VAR support, virtual inertia, etc could help boost system stability. As a good start, tracking the system Eigen value changes with changing inverter control strategies can help get a better understanding of the potential of this technology.

- Power system detailed models: Our current work was limited to the power systems classical network reduced model which resulted in a system with dynamics modelled using ODEs. While this approximation has shown to be effective in capturing first swing instabilities, a more detailed system model is important in order to truly capture the problems with renewables. The resulting system will be modelled as a DAE with larger number of states as compared to the reduced version. The most popular approaches when analyzing the stability of DAE systems using direct methods are singular perturbation and regularization of vector fields. A first step in this direction could be in exploring the variable transformations to convert to a polynomial system with the constraint being the resulting SOS problem's dimensionality.

- Dealing with large scale systems: One of the biggest drawbacks of the SOS techniques is the high computational requirements. In its current form, this limits the size of the power system that can be dealt with. In this regard, the idea of decomposition using a vector Lyapunov function can be explored. This idea is applicable for large interconnected systems like a power system where the system can be decomposed into independently stable subsystems. The SR for each subsystem is estimated independently and then modified in order to account for the coupling with other systems. These lower dimensional SR estimates together makeup the SR in the overall high dimensional state space. One challenge when dealing with a large system with LVRT constraints would be in how to optimally deal with LVRT constraints that couple various subsystems.

- Practicality of risk of instability: The first limitation of the proposed idea is that while for fairly lower dimensional systems, the stability regions can be visualized, for larger systems, it is difficult to relate to them. Therefore, there is a need for scalar metrics that truly reflect the increase in risk due to PVs tripping. One option could be, using the proposed stability region estimates to evaluate the changes in CCTs for a set of faults which is a more relatable quantity. Thus, the operator would be presented with options for PV blocking that result in the maximum increase in CCTs across critical faults.

- Improving CSR estimate: When estimating the CSR under the LVRT constraint modelled using an auxiliary system, it was noticed that the feasibility region was narrowest near the SEP of the auxiliary system and grew wider as we moved away from it. A variable center for the expanding interior region failed as well. A good start to the research could be in exploring the applications for rational Lyapunov functions for approximating CSRs through SOS which has shown promising results in estimating more complex regions [102]. Also, the impact of the studied disturbance may not be felt by the PVs all over the network. In those cases, the constraints corresponding to those PVs can be relaxed further increasing the size of the feasible region however at an added risk to reliability of the results.

- Impact of PV on voltage dynamics: While one of the focus of this work was to understand the implications of displacing conventional generation by PV on the angular stability, the other equally important problem is to study the impact on voltage security and stability.

Reducing conservativeness in nested invariant sets: We presented a sequential estimation approach to estimating the SR under a fixed cascading sequence. The conservativeness in this strategy is inherently increases for cases with increasing number of nested sets to be found. One option is to use start with the estimate from the sequential algorithm and then expand the innermost set while keeping the outer sets as variable, effectively an expanding interior algorithm with more than two regions

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