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Power System Voltage Collapse Mitigation Employing Optimization Based Dynamic Voltage Stability Analysis

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Abstract

Maintaining voltage stability is an important factor in modern power system study and operation. Supplementing the system with Volt Ampere reactive (VAr) power support devices such as the Flexible Alternating Current Transmission Systems (FACTS) helps to overcome voltage instability issues. Commonly, the dynamic optimization-based method is employed to study the dynamic Voltage Stability Analysis (VSA) of the system. The existing dynamic optimization approach has dependencies on the availability of specific tools and the FACTS model to perform dynamic VSA. Besides, the application of the existing method for the voltage collapse phenomenon is not addressed in detail. It is desirable to have a generic dynamic VSA approach that does not have dependencies on specific tools and the FACTS model. This paper proposes a new generic approach to carry-out dynamic VSA with any given DAE tool. A method of emulating the FACTS device's behaviour for dynamic VAr injection is introduced using an incremental optimization approach. A generic interface is newly developed as a Modifiable Off The Shelf (MOTS) component to couple the DAE solver and optimization solver. The existing approach is enhanced into a generic dynamic optimization framework by integrating an incremental optimization technique and the generic interface. Voltage collapse phenomenon on IEEE-9 bus system is investigated employing the enhanced framework. Post contingency behaviour of the system illustrates the successful mitigation of voltage collapse issues. Obtained results show the effectiveness of the new generic approach in performing dynamic VSA.

Author Keywords: Voltage collapse, MiPower®, optimal VAr, optimization, dynamic analysis

Type: Research Article

1. Introduction

The power system is a non-linear dynamic system that is highly complex. The stability of the power system is of paramount importance in power system planning and functioning (Taylor 1994). In recent decades, voltage stability has been an important factor in power system planning and operation. The concerns are due to growing system loadings and open transmission access pressures as revealed by several serious incidents around the globe (IEEE 2002; IEEE 2007). In voltage stability studies, two types of techniques used are static and dynamic (Kundur 1994). Static analysis methods employ a steady-state model or a linearized dynamic model. The widely used static analysis techniques of voltage stability are simple but do not provide information on voltage instability dynamics. In dynamic analysis, to solve nonlinear Differential and Algebraic Equations (DAEs) of the power system, time-domain simulations are performed (Paramasivam et al 2013). Static analysis methods are suitable where the voltage stability limits are to be determined for pre-fault and post-fault conditions. However, dynamic Voltage Stability Analysis (VSA) is required to understand the sequence of events that bring about instability immediately after the contingency (IEEE 2007).

The voltage stability issues originate in the system owing to a deficiency of reactive power. As reactive power cannot be transferred, it has to be provided locally by installing Volt Ampere reactive (VAr) resources at identified locations. During planning studies, it is crucial to figure out the size of the VAr resources that work economically and serves the purpose of mitigating the voltage stability issues. The optimal sizing of VAr resources to achieve steady-state voltage stability has been an extensively researched area. A significant amount of literature is available to study the static voltage instability problems and methods (Kessel and Glavitsch 1986; Gao, Morison, and Kundur 1992; Ajjarapu and Lee 1998; Zhang et al 2007). The recent literature on static voltage stability includes the application of Improved Particle Swarm Optimization and Recursive Least Square Hybrid Algorithm (IPSO-RLS) to determine the static voltage stability region (S. Maihemuti et al 2021). However, optimal sizing of VAr resources concerning dynamic voltage stability has been gaining momentum only in the last few years. Determination of optimal VAr to achieve dynamic voltage stability is a complex problem because it is a nonlinear optimization problem that requires the post-contingency voltage path of the power system (Huang et al 2014). The study involves a nonlinear optimization tool and a tool for solving DAEs of the power system. The Voltage stability indices such as the Transient Voltage Severity Index (TVSI) and Voltage Collapse Proximity Indicator (VCPI) are employed in the optimization model to study the voltage instability phenomenon (Y. Chi, Y. Xu and R. Zhang 2021). If the system dynamic equations and optimization are to be solved together, it becomes computationally intensive. Also, it may pose convergence issues when applied to large systems (Huang et al 2014). To overcome the above challenges, (Paramasivam et al 2013) proposed a dynamic optimization-based approach employing PSS®E and MATLAB® as DAE and optimization tools respectively, where the system dynamic equations and optimization are solved separately using built-in Application Program Interfaces (APIs). Authors have considered the scenario of voltage dip and slow recovery due to the Fault-Induced Delayed Voltage Recovery (FIDVR) phenomenon (Paramasivam et al 2013). The study time of interest considered is 5 seconds. The similar set-up, scenario, and study time are adapted in several other works but with different optimization techniques. In (Huang et al 2014), optimal VAr is determined through a linear programming method. A heuristic approach is followed to initialize the optimization variables. The approach followed requires the knowledge of post fault voltage trajectory of the system. Initial values of optimization variables are guessed such that they meet all the post fault criteria. In (Huang et al 2017), optimal dynamic VAr size is achieved through the Voronoi diagram-based algorithm. In (Huang et al 2017), optimal dynamic VAr size is achieved through the mesh adaptive search method. Non-dominated sorting genetic algorithm II (NSGA II) is employed to determine the Pareto Front for VAr size (J. Liu et al 2018; Y. Chi, Y. Xu and T. Ding 2020).

From the literature, it is observed that the dynamic optimization is carried out with PSS®E as a DAE solver. The Flexible AC Transmission Systems (FACTS) model provided by PSS®E is employed for dynamic optimization. Study parameters are fetched through the ready-made APIs available in the PSS®E tool. Studies reported are mostly on the FIDVR issues. It is observed that the existing approach has a dependency on the availability of a specific tool to perform dynamic VSA. It is found that there are limited case studies on detailed analysis of voltage collapse scenarios employing dynamic optimization.

To perform dynamic VSA with any given DAE tool, the availability of a generic approach devoid of dependencies is a prerequisite.

This paper introduces a generic framework to carry out the dynamic VSA with a given DAE solver. An incremental optimization technique is proposed to simulate the behavior of the FACTS device for dynamic VAr injection. A new generic interface is developed to link the DAE solver and optimization tool.

The following are the paper's main contributions:

a) An incremental optimization-based method is introduced to mimic the functionality of the FACTS device. To enable dynamic VAr injection emulating FACTS device, minimization of incremental VAr is employed as the objective function. Constraints are applied on incremental VAr.
b) Development of a new interface as a Modifiable Off The Shelf (MOTS) component linking the optimization solver and DAE solver. The developed interface has data extraction and data transformation capabilities. The data extraction capability of the developed interface is customizable for a DAE solver.
c) Detailed analysis of voltage collapse phenomenon on IEEE-9 system by integrating incremental optimization technique and the generic interface into an enhanced dynamic optimization framework.

This paper is structured as follows. Section-2 presents the methodology of the dynamic voltage stability analysis. Section-3 presents the results and discussions on the application of the suggested generalized approach to the IEEE-9 bus system. Conclusion and scope for further work are presented in section-4.

2. Methodology

In this section, high-level architecture, optimization model, candidate selection for VAr support, and voltage criteria are described. The proposed generalized approach for dynamic voltage stability analysis is elaborated.

2.1. High-level architecture

The high-level architecture consists of an Optimization block, DAE solver block, and Interface block as shown in Figure 1.

Optimization block refers to MATLAB®. DAE solver block refers to MiPower® software. MiPower® is a Windows-based power system analysis toolbox with steady-state and dynamic analysis capabilities (MiPower® homepage-2022). The TRS module of MiPower® is employed as a DAE solver to perform time-domain analysis. A generic MOTS interface component is newly developed to link the DAE solver and optimization tool. The interface component performs raw data extraction from the DAE solver, and data transformation and enables data exchange between the DAE solver MiPower® and the optimization solver MATLAB®. The optimization block determines the optimal VAr employing the fmincon algorithm. In short, the architecture supports the following functionalities.

- Connect MATLAB® and MiPower®

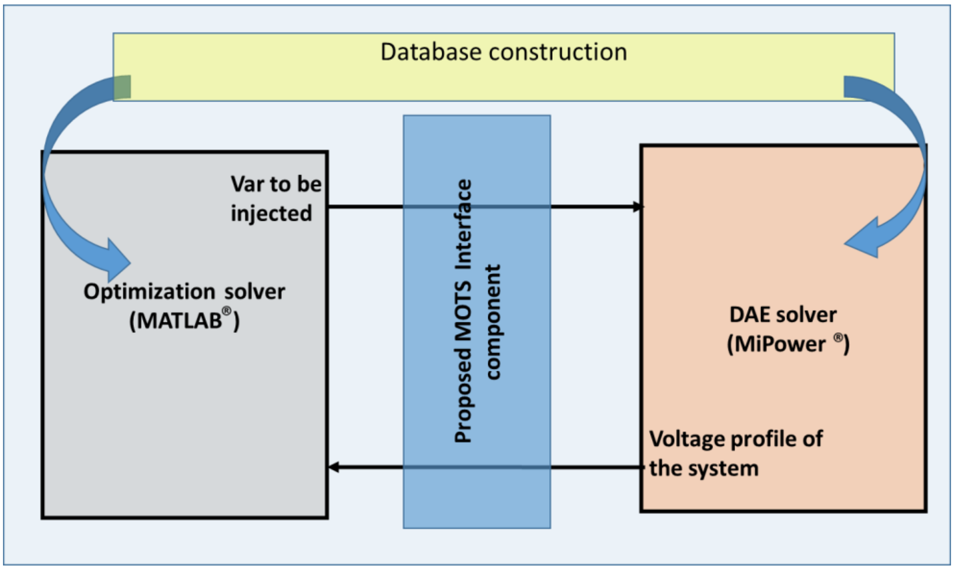

Figure 1: Architecture of the employed methodology based on (Paramasivam et al 2013)

- Data extraction and transformation
- Emulate dynamic VAr injection

The optimization model employed by the optimization block is presented in the following section.

2.2. Optimization model

The Incremental method of optimization is introduced to simulate the dynamic VAr injection behavior of the FACTS device. With the incremental optimization technique, an optimal solution is determined time-step wise and the solution for the subsequent time steps is incrementally determined based on the solution of the preceding time step through which a trajectory of the feasible solution is developed (Jeffrey 2008). The VAr value obtained from the optimization is directly injected into the system as reactive power compensation emulating the FACTS functionality. At each time step, the decision to trigger VAr injection is based on the voltage status of the buses at that time step. If the bus voltage is within limits, additional reactive power compensation is not activated. If bus voltages violate the stipulated criteria, optimal VAr injection is activated. The objective of the optimization is to determine the minimal incremental change in VAr required to improve the voltage profile from the current levels, subjected to voltage constraints and incremental VAr constraints. The optimization model employed is indicated in Expressions (1) – (5). It is distinct from the model employed in (Paramasivam et al 2013) in the following aspects:

- Incremental VAr $\Delta Qk(t)$ is employed in objective function and constraints
- Equations (4) and (5) are newly introduced

Above modifications enable emulation of time step-based dynamic VAR injection into the system. The variable Vio (t) represents the voltage at a bus i at a current time step considering the VAR injection provided to the system at the previous time step.

$$\text{Minimize } \Delta \text{Qk} \quad \sum_{k=1}^{Nc} \sum_{i=1}^{Nt} \frac{\partial Vi(t)}{\partial Qk(t)} \; \Delta Qk(t) \tag{1}$$

$$Vi_{min}(t) \leq V_{io}(t) + \sum_{k=1}^{Nc} \frac{\partial Vi(t)}{\partial Qk(t)} \Delta Qk(t) \leq Vi_{max}(t) \quad \textbf{(2)}$$

$$\Delta Qk_{min} \leq \Delta Qk \leq \Delta Qk_{max} \quad \textbf{(3)}$$

$$Q_{CurrentTimeStep,k} = Q_{PreviousInjectionTimestep,k} \text{ , if } V_{min,i} \leq V_i \leq V_{max,i} \quad \textbf{(4)}$$

$$Q_{CurrentTimeStep,k} = Q_{PreviousInjectionTimestep,k} + \Delta Q_{CurrentTimeStep,k} \text{ , if } V_{min,i} \nleq V_i \nleq V_{max,i} \quad \textbf{(5)}$$

where

$\frac{\partial Vi(t)}{\partial Qk(t)}$ is the change in voltage at i^{th} bus resulting from VAr injection at bus k.

$\Delta Qk(t)$ is the incremental change to VAr at time instance t at bus k.

Vio (t) is the voltage (RMS) at i^{th} bus without compensation at time instance t.

$Vi_{min}(t)$ and $Vi_{max}(t)$ are the minimum and maximum values of RMS voltage defined as per the criteria at bus i at time instance t.

ΔQk_{min} and ΔQk_{max} are the minimum and maximum values of incremental changes to VAr injections.

Nt is the total number of buses in the system.

Nc is the number of candidate buses in the system.

$Q_{CurrentTimeStep,k}$ is the total reactive power injection at bus k at a given time step.

$Q_{PreviousInjectionTimestep,k}$ is the total reactive power injection at bus k at the preceding time step.

Voltage criteria employed in the dynamic VSA are presented in the following section.

2.3. Voltage criteria

To avert voltage instability issues, the system must adhere to the well-established voltage criteria.

The transient stability voltage criteria recommended by WECC/NERC(Western Electricity Coordinating Council, North American Electric Reliability Corporation) for N-1 contingency (Shoup, Paserba, and Taylor 2004) are considered.

According to these criteria (Huang et al 2014):

C1: Post-contingency voltage should be within 25% at load buses, 30% at non-load buses

C2: Post-contingency voltage should not be more than 20% more than 20 cycles

C3: Post-contingency voltage after $t_{settling}$ seconds should not settle exceeding 5%

Based upon the voltage limits imposed by the above criteria, dynamic voltage stability analysis is carried out in three timeframes T1, T2, and T3. Figure 2 depicts the voltage envelope incorporating the criteria. The instance t_i refers to the first time instance post the

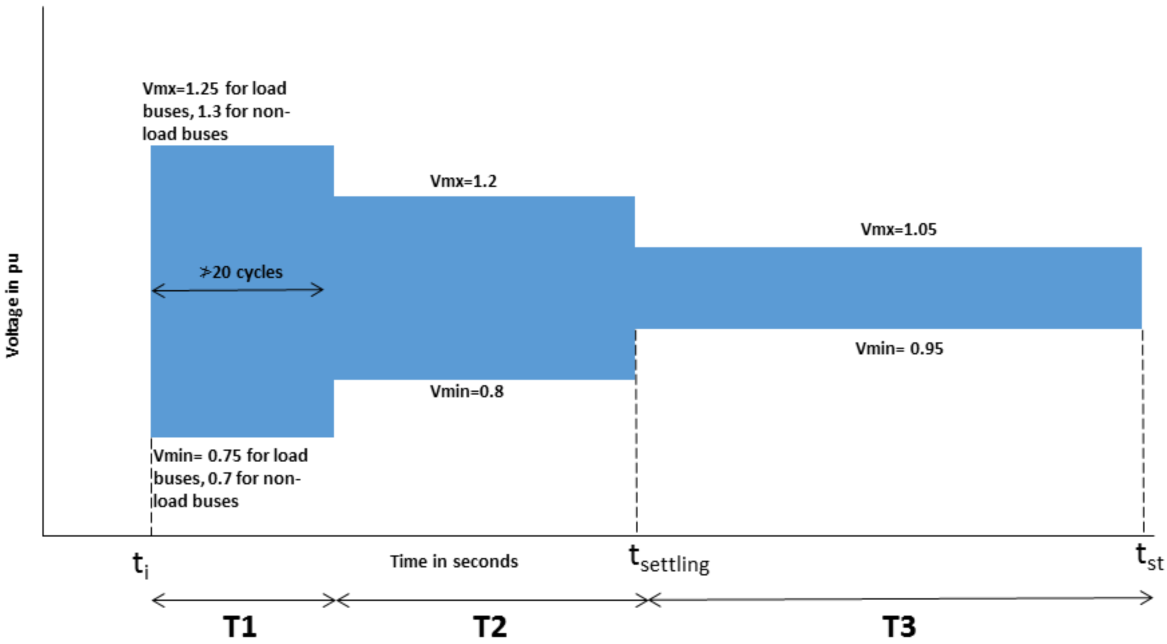

Figure 2: Envelope of transient voltage criteria based on (Shoup, Paserba, and Taylor 2004)

fault clearance when the C1 criteria are violated. From the beginning of instance $t_{settling}$, the bus voltages should not exceed 5%. The instance t_{st} refers to the study time of interest.

The location of the VAr resource has a bearing on the voltage stability of the system. The method to determine the candidate locations for VAr injection is presented in the next section.

2.4. Determination of candidate buses for VAr injection

Candidate buses for providing the reactive power support is determined using sensitivity analysis employing Trajectory Sensitivity Index (TSI) [Sapkota, Bishnu, and Vijay Vittal 2010]. For a small amount of VAr injection at bus j, the change in voltage profile of other i buses is determined. TSI values of the buses are computed employing the Formula 6 (Sapkota, Bishnu, and Vijay Vittal 2010)

$$\mathrm{TSI_i} = \sum_{k=1}^{Tk} Wk \sum_{i=1}^{N} Wbi \left[\frac{\partial Vi}{\partial Qj}\right] \qquad (6)$$

Where,

TSI_j → Trajectory sensitivity of bus j

$\frac{\partial Vi}{\partial Qj}$ → Sensitivity at bus i due to change at bus j

Wbi → Weight of bus i

W_k → Weight of time instance

Tk → Number of time instances considered

N → Number of buses

Buses with high TSI values are considered candidate locations for VAr injection (Sapkota, Bishnu, and Vijay Vittal 2010)

The new generalized approach employed to carry out dynamic VSA is presented in the following section.

2.5. Generalized dynamic voltage stability analysis framework

The dynamic optimization framework presented in (Paramasivam et al 2013) is enhanced into a new generalized approach for performing dynamic voltage stability analysis. The enhanced approach is free from dependencies on the availability of a specific DAE tool for performing dynamic VSA. Dependency is overcome by developing the generic interface and by introducing an incremental optimization technique. By applying the new generalized approach, dynamic VSA can be performed with any given DAE tool. The algorithm and the flow chart for the new generalized approach are presented in this section.

2.5.1. Algorithm

a) The system database file is prepared. Optimization parameters and constraints are specified.
b) Timeframe T1 is defined as the current timeframe. The time instance in the current timeframe at which voltage criteria are violated is identified.
c) At the violated instance, a small amount of reactive power Δq is injected at candidate location k to determine the sensitivity at other i buses.
d) A dVi/dΔq sensitivity matrix is formulated.
e) The sensitivity matrix along with the bus voltage profile is used by the optimization solver to compute the incremental optimal VAr.
f) The incremental optimal VAr is injected into the system at candidate locations and compliance with voltage criteria is checked.
g) Steps (c) to (f) are repeated till the voltage criteria are satisfied for that instance
h) The succeeding instance of violation in the current timeframe is identified.
i) Steps (c) to (h) are repeated till all instances of the current timeframe are covered.
j) The succeeding timeframe is defined as the current timeframe and corresponding voltage criteria are applied. The first instance of voltage criteria violation is identified.
k) Steps (c) to (j) are repeated till timeframe T3 is completed.

2.5.2. Flowchart

Figure 3 presents the flowchart of the proposed generalized approach. The flow chart depicts the program flow across the Optimization block, Interface block, and DAE solver blocks in detail. In the set-up phase, the database is constructed and constraints are defined. The maximum and minimum VAr injection limits are specified as Qmin and Qmax. Initial incremental VAr injection is specified as zero which corresponds to the scenario of no compensation. Voltage criteria for the buses are defined for the three timeframes as Vmin and Vmax. In the execution phase, the newly developed interface enables automated back-to-back execution of MiPower® and MATLAB® from timeframe T1 to T3. The new interface extracts and transforms the study parameters from MiPower® into the form required for optimization. The functionality of the newly developed interface is comprehensively illustrated in the Interface block. Results obtained employing the generalized approach are presented in the next section.

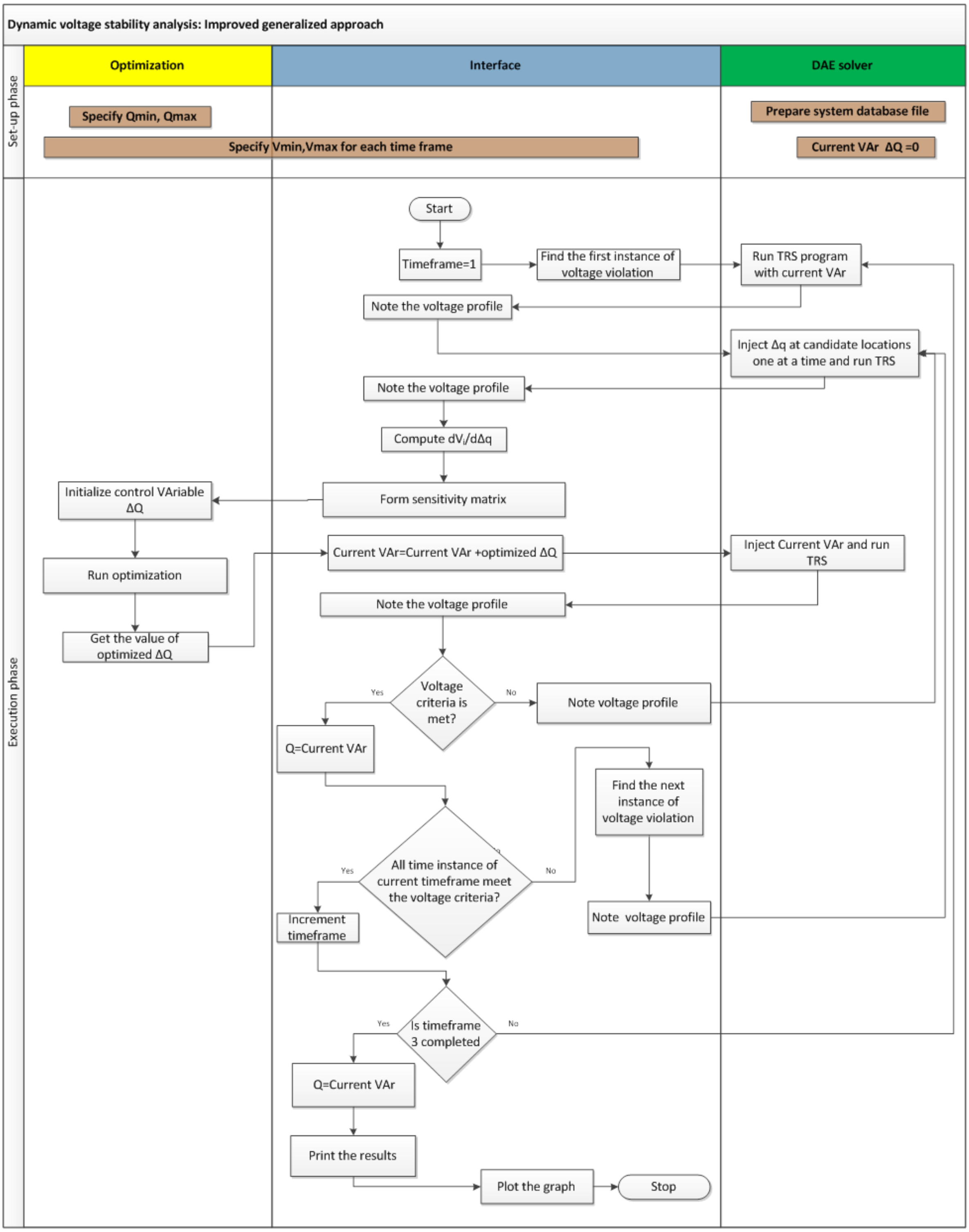

Figure **3**: Flowchart of generalized approach for dynamic voltage stability analysis

3. Results and discussions

By employing the generalized methodology proposed in section 2, dynamic VSA is performed on IEEE- 9 bus system. The single-line diagram of the system is illustrated in Figure 4.

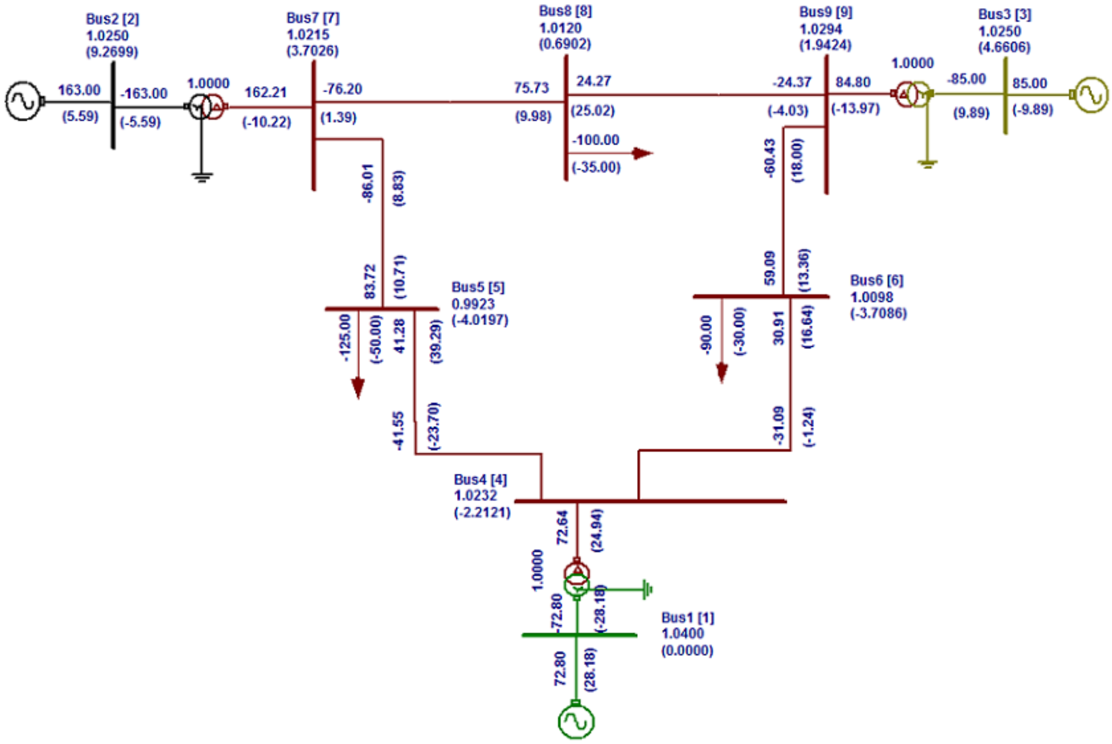

Figure 4: IEEE- 9 bus system ((MiPower®-2022).

A three-phase to ground fault is applied at 0.2 s on bus 7. The fault is removed by opening the line between bus 7 and bus 5 at 0.3 s. The resulting voltage profile of the system after the fault clearance is presented in Figure 5. Figure 5 corresponds to the behaviour of the system without VAr support. It can be observed that bus voltages have initially improved to above 0.75 p.u. levels after clearing the fault. However, a continuous decline in bus voltages is observed from 0.52 s onwards leading to a steep decline around 0.9 s resulting in voltage collapse at around 0.94 s. This implies that VAr support is required for the system to be voltage stable. To determine the VAr support initiation instance, the first instance after the voltage recovery where the bus voltage has exceeded the 20% norm is considered. It can be observed from Figure 5 that at 0.49 s, bus voltage has breached the 20% norm. It has declined to below 0.8 p.u. levels. This instance is considered as the t_i, the start of the T1 timeframe. The duration of the T1 timeframe considered is 18 cycles. Accordingly, the T1 timeframe lasts till 18 cycles counting from t_i after which the T2 timeframe starts. The T3 timeframe starts at 3 seconds after the fault clearance. The analysis time of interest t_{st} is 50 seconds. The time step interval is defined as 0.01 s. Buses 6 and 8 are considered as two candidate locations for VAr injection based on TSI values indicated in Table 1.

The generalized approach presented in section 2.5 is applied to calculate the optimal VAr required to meet the voltage criteria. Table 2 presents the results obtained. The column 'VAr at buses' refers to the location of the VAr support. The columns 'Minimum' and 'Maximum' refer to the range of the VAr support required along the post contingency path of the system. The size of VAr at bus 6 and bus 8 is 54.44/104.89 MVAr and -81.68/101.22 MVAr respectively. Reactive power support requirement at the candidate locations varies between the minimum and maximum values as shown in Table 2. The resulting voltage

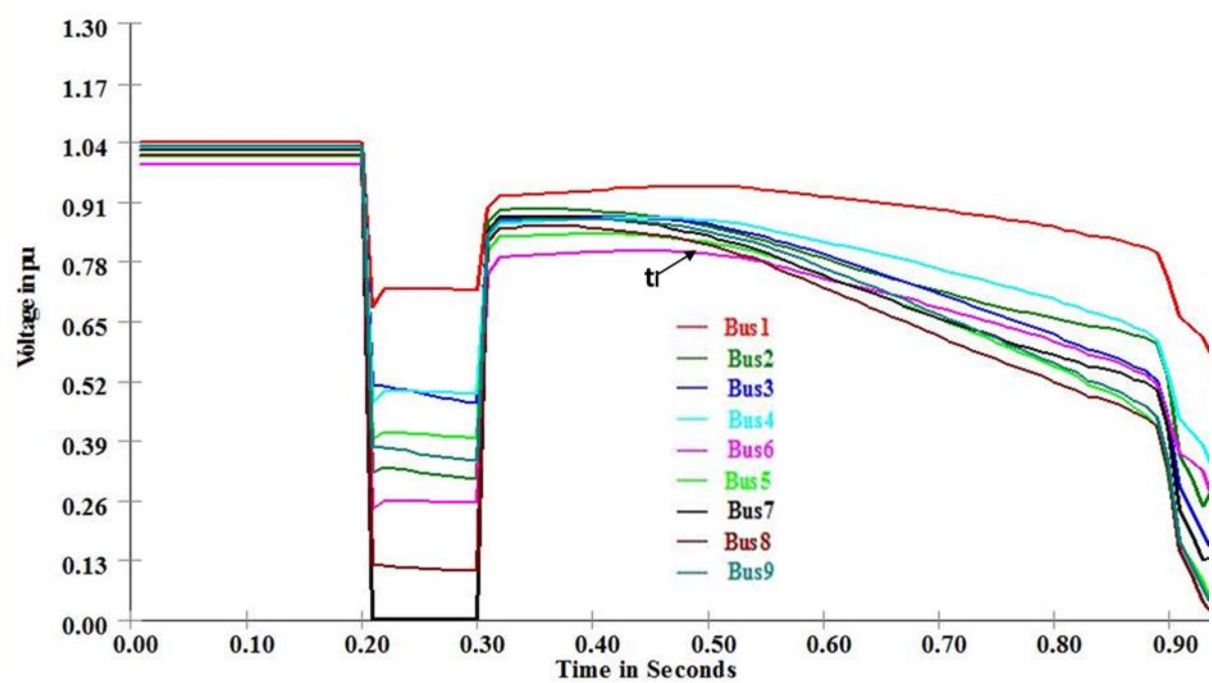

Figure 5: Voltage profile after 3 phase fault at bus 7 without VAr support

profile of the system with the injection of dynamic VAr is shown in Figure 6. Compared with Figure 5, it can be observed that bus voltages have satisfactorily recovered after the fault clearance. Voltage criteria are satisfied for the T1 and T2 timeframe. In the T3 timeframe, voltage criteria are satisfied only till 7.1 seconds. At 7.2 s, even with the VAr support, voltage criteria do not comply for bus 5. It is observed that in this instance, some of the buses are at either lower voltage limit or upper voltage limit. That is, bus 5 voltage is at 0.949 p.u. The voltage levels of bus 6 and bus 9 are 1.049 p.u. and 1.048 p.u. respectively. Further optimization iterations satisfy either the bus 5 criteria or bus 6 criteria but not both thereby entering the toggle state. Optimization becomes infeasible due to the toggling issue. To overcome the toggling problem, it becomes imperative to provide VAr support at bus 5 too.

Bus#	TSI value	Rank
5	0.304889	3
6	0.337763	2
8	0.362973	1

Table 1: TSI value of load buses

VAr at buses	Minimum (MVAr)	Maximum(MVAr)
Bus 6(Q6)	54.44	104.89
Bus 8(Q8)	-81.68	101.22

Table 2: Optimal VAr with bus 6 and bus 8 as candidate locations

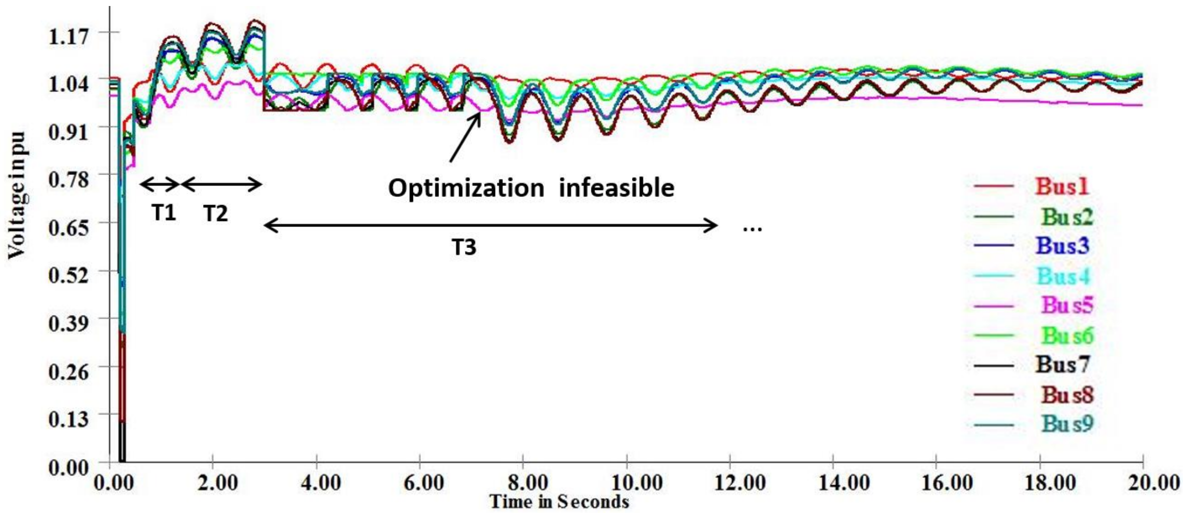

Figure 6: Voltage profile of the system with VAr support at buses 6 and 8

With bus 5 added as a third location in addition to bus 6 and bus 8, the generalized approach is repeated for the three timeframes T1, T2, and T3. Toggling issue is not observed after supplementing the system with VAr injection at bus 5. Optimization becomes feasible and the results of optimization are presented in Table 3. It can be observed that the sizes of Q5, Q6, and Q8 are 10.93/72.64, -31/29.84, and -91.79/133.22 MVAr respectively.

VAr at buses	Minimum (MVAr)	Maximum(MVAr)
Bus 5(Q5)	10.93	72.64
Bus 6(Q6)	-31.00	29.84
Bus 8(Q8)	-91.79	133.22

Table 3: Optimal VAr with bus 5, bus 6, and bus 8 as candidate locations

The resulting voltage profile of the system after providing the reactive power support at bus 5, bus 6, and bus 8 is plotted in Figure 7. By comparing Figure 6 and Figure 7, it can be noted that after providing the reactive power support at three locations, the behaviour of the system has improved. Bus voltages have not only satisfactorily recovered post fault in the T1 and T2 timeframe, but also have complied with T3 timeframe criteria. Post contingency voltage profile of the system has significantly improved and voltage collapse of the system has been effectively mitigated. Table 4 provides the comparison of results with and without bus5 as candidate location.

# of locations	Candidate locations	Total MVAr (Capacitive)	Total MVAr (Inductive)	Result
2	Bus 6, Bus 8	206.11	-81.68	Infeasible
3	Bus 5, Bus 6, Bus 8	235.72	-122.80	Feasible

Table 4: Comparison of results

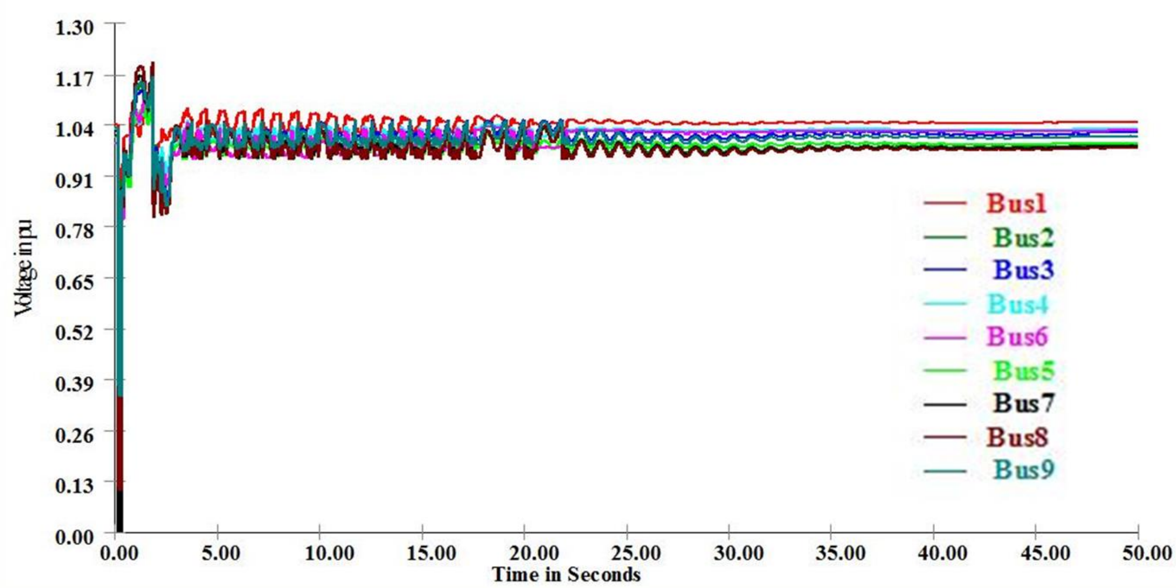

Figure 7. Voltage profile after 3 phase fault at bus 7 with VAr support at bus5, bus 6, and bus 8

Table 5 summarises the actual performance of the system with reference to the defined voltage criteria after providing the VAr support at three locations. The 'Expected performance' column corresponds to the criteria specified by WECC/NERC. The 'Actual performance' column corresponds to the behaviour of the system after providing the reactive power support at bus 5, bus 6, and bus8.

Criteria	Expected performance	Actual performance	Status
C1	Post-contingency voltage limit should not be more than 25% at load buses and 30% at non-load buses.	Post-contingency bus voltages are between a lower limit of 0.8 p.u. and an upper limit of 1.2 p.u.	Criteria are satisfied
C2	Post-contingency voltage should not exceed 20% more than 20 cycles.	1. Actual performance is better than the expected performance with respect to the number of cycles. The standard allows the post- contingency voltage to exceed 20% up to 20 cycles. Actually, post-contingency voltage levels have not exceeded 20% for more than 18 cycles 2. Post-contingency bus voltages are between a lower limit of 0.8 p.u. and an upper limit of 1.2 p.u.	Criteria are satisfied
C3	Post-contingency voltage after $t_{settling}$ seconds should not settle exceeding 5%.	Post-contingency, steady-state voltages have settled between a lower limit of 0.95 p.u. and an upper limit of 1.05 p.u.	Criteria are satisfied

Table 5. Summary of the system performance with VAr support at bus5, bus 6, and bus 8

4. Conclusions and Future Scope

In this research, an incremental optimization technique is introduced to simulate the behavior of the FACTS device for dynamic VAr injection. The newly developed interface enables seamless coupling of the given DAE tool and optimization tool. The incremental optimization model and the new interface are integrated into a new generalized framework to perform dynamic VSA. The generalized approach is verified on IEEE- 9 bus system with a voltage collapse scenario. Test conditions include compliance to WECC/NERC transient voltage criteria. Candidate locations for providing VAr support are identified using the TSI method. Obtained results prove that the generalized approach has aided the coherent linking of the DAE solver and optimization solver. The optimal VAr values obtained from the generalized approach have been utilized to study the voltage behaviour of the system. It is observed that even with VAr support at bus 6 and bus 8, the system is not meeting the voltage criteria for the T3 timeframe. To achieve the expected voltage levels, supplementing VAr support at a third location such as bus 5 is necessitated. With the VAr support at bus 5, bus 6, and bus 8, the voltage level of the system is improved and voltage collapse is effectively prevented. All the bus voltages have recovered to the prescribed levels satisfying the specified voltage criteria. Injection of optimal VAr determined by the generalized approach has enhanced the voltage stability of the system. Results demonstrate that the generalized approach enhances the existing capability of the DAE solver to perform dynamic voltage stability analysis. The advantage of the generalized method is that with minimal customization effort, it can be employed with any DAE solver to perform dynamic VSA.

As a part of the future scope, the generalized approach will be applied to a practical power system to perform dynamic voltage stability analysis.

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