Power System Transient Stability Analysis on Algorithmic and Performance Metrics

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***Abstract*— The majority of TSA techniques often do the set of examinations on the simulated network system for assessing the power system's stability properties. Nevertheless in certain cases, especially during fault constraints, thorough knowledge of the network might not be fully presented. In this work, 20 research works are reviewed for analyzing the TSA. The analysis results are given under some categories: algorithmic analysis, performance measure and the achieved the best measure as well.**

Keywords—TSA; Power System; Stability property; Voltage; Transmission system

Nomenclature

Acronym	Description
TSA	Transient Stability Analysis
FACTS	Flexible AC Transmission Systems
SVCs	Static Var Compensators
TCSCs	Thyristor Controlled Series Capacitors
DAE	Differential and algebraic equations
PEBS	Potential energy boundary surface
SPM	Structure preserving model
DAEs	Differential-algebraic equations
VSC	Voltage source converter
COT	Center of inertia
DFTGs	Doubly fed induction generators
PWR	Pressurized-water reactor
CFETR	China fusion engineering test reactor
DFIGF	Doubly fed induction generator with flywheel
UPFC.	Unified power flow controller
CCT	Critical clearing time
CM	Critical moment
SMES	Superconducting magnetic energy storage
GVs	Gridable vehicles
CFS	Cascading failure simulators
HS	Hybrid System

I. INTRODUCTION

POWER system is defined as the gathering of devices, which produce transmit as well as distribute energy for the consumption of units like factories, housing buildings along with avenue lighting. Recently, the power system modernization is becoming an interesting factor that also increases the generation of renewable power and the consumption of measurement and monitoring infrastructures. Even though, these developments generate effective and eco-friendly infrastructures (energy), the consequent stochastic activities in transmission production and distribution systems are additionally difficult with power system TSA issues or problems. Most of the TSA [20] models perform the set of examinations on the simulated network system to evaluate the power system's stability properties. Nevertheless, in certain aspects, especially at the time of fault conditions, detailed network knowledge might not be completely available. In industries, the usual manner of examining TSA [8] of a power system is allowing the system to run broadly time–domain simulations for vital fault strategy. The respective manner of enhancing action plans for the transient stability upholding is simpler as well as practical if the "important" scenarios are known for the consideration. Unluckily, power systems are huge scale systems, and hence the count of feasible circumstances is moderately huge.

Since the extensive explore of those respective situations is unfeasible, power engineers require guessing the vital bags that they required for analyzing process. Generally, the power systems were greatly enhanced with multifaceted dynamics and nonlinear dynamics. This could have different operation views. Consequently, the nonlinearity turns more outstanding at possibility. For this situation, the existing controllers are inappropriate, but they are best in single operating point. Number of works has been takes place by the power system engineers. Nowadays, FACTS are successfully employed for mitigating the problem of power system stability.

This paper gives a deep survey on TSA algorithms. 20 papers are reviewed, and the papers are reviewed in terms of performance analysis, methods used and best values. The rest of the paper is ordered as follows: Section II reviews the literature work. Section III details the Analytical results. Section IV concludes the paper.

II. ANALYSIS ON DIFFERENT CONTRIBUTIONS

A. Related Works

In 2017, Gou *et al.* [1] have presented a new relative energy function (pair-wise) for the analysis of real transient stability along with the emergency control. In this, the developed energy control could accurately find the critical and non-critical clusters than the conventional methods. In addition, they have developed a new emergency control for stabilizing the founded critical generators in a petite period after the clearance of fault. The approach could evaluate the vital generation limitation capacity through the pre-evaluated relative system energy. At last, the relative energy oscillation, which arises in the significant cluster was used for locating the most suitable generator for launching the emergency control. Finally, the proposed model was compared to the conventional methods, and it has reviewed that the proposed model could be practically applied for the analysis of transient stability.

In 2014, Caliskan and P. Tabuada [2] have stated that forcing all the voltages and currents with the correct frequency is considered as the most vital issue in the field of power systems, which was also called the transient stability problem. Number of classical approaches was used for examining the transient stability, which were on the basis of numerous implicit assumptions. One of the assumptions was the phases usage for the examination of transients. This research work has used energy-based approaches that were derived from 1st principle. Additionally, for eliminating the assumptions that were unknown to hold while transient stages, they have

derived the intuitive constraints that assuring the power systems' transient stability with lossy transmission lines.

In 2012, Hamidifar and N. C. Kar [3] have proposed a novel new trigonometric algorithm for representing the electrical machines' saturation characteristics that was on the basis of saturation data points. The proposed approach could apply to different kinds as well as electrical machines sizes. Then, the evaluated outcomes have demonstrated the efficiency of developed approach. This respective trigonometric approach has been engaged for the existing synchronous machine approach, and subsequently, the performance analysis was also takes place. Further, the investigation outcome has revealed the betterment of proposed model over others in terms of saturation inclusion in stability analysis.

In 2018, Asim *et al.* [4] have proposed a new non-linear control approach like TCSCs for analyzing the multimachine power system transient stability. The formulation of TCSC controller was carried out by Zero dynamic design model. For testing purpose, the authors have used a type 3-machine 9-bus system in which 2 counts of TCSC controllers were located near to the networks' greatest load bus. The attainment of system's dynamic stability was done through the investigation of internal states stability and the system's external states. The assurance of stability internal states was made via the Lyapunov stability theorem. The comparison of proposed work was made with some other existing design on the basis of approximate linearization approach. Further, the impact of different operating points was investigated under various loading constraints.

In 2018, MarcoLindner and RolfWitzmann [5] have established two accurate inverter approaches featuring local Q(V), voltage control: a Simulink approach (non-linear) and a least signal approach. Further, the non-linear approach could be utilized for performing transient events arbitrary analyses, the purpose of small signal model was the incorporation of grid models for studying the least signal stability and feasible interactions. All these approaches were build bottom-up from grid filter as well as PWM, and the Q(V) was designed in the components of dq0. The authors have used the high resolution laboratory metric for the verification as well as the parameter designing for the assurance of reproducibility. The proposed small or least signal approach could be interpreted as the dynamic admittance, and hence it could be very simple to include in the analysis of power system

In 2015, suji *et al.* [6] have stated that as the power systems were becoming more higher and difficulty, it was becoming more complex to resolve DAE in the practical time for the operations of system. Particularly, the parallel computing that was on the basis of waveform relaxation approach was the more efficient solution for attaining rapid evaluation for TSA. In order to improve the waveform relaxation model's performance, there needs some suitable partitioning, which was also very much essential. In order to resolve this issue, this research work has proposed a novel partitioning approach, which was better suited for analyzing the weakly damped low-frequency oscillation on the basis of the analysis of eigenvalue. Particularly, they have defined an efficient partitioning, and that could automatically determine the developed index.

In 1998, Liu *et al.* [7] have studied the hybrid transient stability analysis. The respective model has varied from the common classical approach. For instance, they have concerned the arbitrarily voltage-dependent loads, machine approach, and network topology. The criterion for identifying the PEBS on the basis of SPM was initially proven. The corresponding approach was engaged to 6-unit as well as 16-unit systems. This was identified to grant additional reliable stability evaluation over the classical hybrid approach for real usage.

In 2016, Milano [8] have proposed a semi-implicit evaluation of DAEs that has described the power system approaches for the analysis of transient stability. The respective evaluation, if joined to the implicit integration approach has shown 2 related benefits in terms of existing explicit evaluation: (i) minimizing the computational difficulty; and (ii) maximizing the Jacobian matrix sparsity of the system. Further, the developed approach could permit the utilization of null time constants and hence simplified the implementation of DAEs. The performance of the proposed model was compared to other conventional methods on some transmission system and has reviewed the betterment of proposed work.

In 2016, Ortega and F. Milano [9] have presented a energy storage system approach for voltage as well as the analysis of angle stability. The developed solution has permitted the modeling of most usual energy storage modalities by a given set of DAEs. Particularly, this research work has concerned the superconducting magnetic, compressed air, battery energy storage devices and electrochemical capacitor. In order to cope up with different modalities, the developed generalized approach has proven to be more accurate for the stability analysis, since it has included a balanced, fundamental-frequency approach of the VSC. Along with this, the regulators with hard limits were also considered. Finally, the generalized model's transient behavior was compared to basic-frequency balanced approaches. They have also made a case study on the basis of test system (WSCC 9-bus).

In 2016, Liu *et al.* [10] have presented a new COT model for understanding how integrated DFTGs effects the power system transient dynamics. Under this coordinate, they have separated the influence of integrated DFTGs into COT related and distinctive generator related parts (synchronous). This research work has also made the investigation of key factors that effect the COT's dynamic motion and the rotor dynamics of every distinctive generator in terms of DFTG integration. In order to do the further validation, the authors have conducted the comparative simulations on 3 various scenarios with different access locations, DFTG capacities, and the synchronous generators replacement as well. Finally, the outcomes have shown that the COT dynamics and the distinctive generators were affected through the integrated DFTGs by various mechanisms, and that was more sensitive on various DFTG's integration variables.

In 2018, Li *et al.* [11] have stated that the CFETR has the ability to result 50-200 MW fusion power for representing the production of power. The complete fusion power plant structure in the designing of concept was same as the PWR, except the DFIGF were developed for replacing the conventional synchronous generator that utilized in PWR. The fusion plant's heat source was not constant in the mode of long-pulse operation. Thus, it would lead to recurrent inrush in power grid and synchronous generator. Even though the electric heating pressure regulator is high-power that could mitigate the inrush, it has consumed more energy. Moreover, the developed DFIGF have great ability of power regulation and huge energy storage capability that appropriates the application if their exist instability of heat source. Finally, the

simulation work has demonstrated that the proposed DFIGF could grant the flexible connection along power grid.

In 2018, Alam and Q. Ahsan [12] have proposed a mathematical approach that was appropriate for the examination of stability of the concurrent AC–DC transmission system. The respective approach was on the basis of equal area measure principle. The important attribute of this approach was the development of the solution model of integral component. This could avoid the trial as well as error model for the analysis purpose. This development process has considered the single bus system along transmission line that connects both machine as well as infinite bus. This progression has also considered the severe fault in the end bus. The model validation was executed via 2 various models: comparison of the attained outcomes by applying the results developed approach to the power system over other methods and with the attained outcomes by standard software.

In 2018, Ortega and F. Milano [13] have provided a detailed stochastic study of energy storage effect on the systems of transmission grids. The effect was assessed by the consideration of combined impact of various energy storage models, time of fault clearness, as well as network topologies. Subsequently, they have considered the comparative faults positions, storage devices, as well as synchronous machines. Then, the real-time study has included the time-domain simulation on various bus systems.

In 2016, Mohanty *et al.* [14] have presented a comparative learning of transient stability and the issues of reactive power recompense in a HS that was on the basis of autonomous wind-diesel-photovoltaic through the utilization of robust fuzzy-sliding mode. This was actually on the basis of UPFC. The authors have also considered the linearised small-signal approach for the TSA in HS. Along with this, they have concerned the IEEE type 1 system for the HS generators along the characteristics of insignificant saturation to provide better analysis. From the simulation outcome, it was proven that the UPFC performance was better than static VAR compensator in terms of voltage profile. Furthermore, they have designed the fuzzy as well as the fuzzy-sliding form related UPFC controller for improving the performance of transient. Moreover, this simulation results have proven the betterment of proposed system.

In 2015, Roberts *et al.* [15] have derived the analytic approximation for CCT measure from approaches for the power system stability. Then, the authors have designed the formula for incorporating many transient stability features like various fault locations as well as various network states. The major idea of this measure was to do the analysis on trending in stability (with respect to CCT) of power systems on various system parameter deviations. Subsequently, the measure performance on measuring stability trends has been demonstrated on power network. Finally, the designed measure was compared with other CCT expressions that include further nonlinearities exist in the approach.

In 2016, Kim and T. J. Overbye [16] have presented a adapted approach for the analysis of power system's TSA that permits the minimization of computational needs whereas retain vital system dynamics. Further, the respective model has formulated the equations (power balance) that depend on area of interest. Here, the AC approach that includes full reactive, as well as real power equations, were utilized for the area, where the great accuracy is needed. The simpler dc approach that includes real power equation (linear) was utilized for more remote areas. The authors have attained high accuracy rate by the ac model with respect to certain evaluation measures. To avoid the failure of simulation accuracy, this research work has developed a way for compensating line losses ignored by the dc approach.

In 2015, Yan *et al.* [17] have compared the typical DC power flow-based CFS validity in the analysis of cascading failure along a novel arithmetic measure that termed as the CM. Subsequently, the modified CFS was initially implemented for simulating the behavior of system after the first contingencies and also for evaluating the usage of DC-CFS in the analysis of cascading failure. Afterward, the DC-CFS was compared over other classic stability models. They have introduced the CM with a case study for assessing the use of two approaches for cascading failure analysis. Then, the simulation outcome has revealed the vital consistency as well as discrepancy among 2 models.

In 2012, *Wu et al.* [18] have developed the transient stability analysis of power grid that has integrated SMES as well as GVs. Further, the operation of vehicle-to-grid (V2G) was devised for controlling GVs to do the grid charge or grid discharge. The authors have takes place the simulation work on different faults on various SMES as well as V2G power penetration proportions. The outcomes of load angle response were given for illustrating both SMES as well as GVs, which could enhance the power grid's transient stability. Further, the concurrent usage of GVs, as well as SMES, could further enhance the performance of system dynamic.

In 1978, enkataramana and L. Jenkins [19] have applied the approach of diakoptics to the transient stability analysis. They have used the Diakoptics for obtaining the power flows of transmission line that were needed in the step-by-step approach. Finally, by this model, the stability studies of huge power systems have been studied.

In 2009, Xyngi *et al.* [20] have described the TSA of a 10-kV distribution network along microturbines, and other plants. Further, the network that moulded in Matlab/Simulink has considered the thorough generators dynamic models. The authors have investigated the fault simulations at different locations. The outcomes that were obtained from different case studies have presented and discussed.

III. Analytical Results

A. Algorithmic Analysis

This section describes the algorithmic analysis from the reviewed works. In this, new pair-wise relative energy function is introduced in [1]. the authors of [2] have proposed Energy based TSA model. then, the new trigonometric algorithm is developed in [3]. In [4], the authors have developed the non-linear control scheme. Non-linear Simulink model [5] is the new algorithm of association rule mining. In [6], the authors have developed a partitioning method. A structure preserving model (SPM) is developed in [7]. Semi-implicit formulation of the DAEs is developed in [8]. A energy storage system approach is used in [9]. The COI approach is developed in [10]. DFIGF is proposed in [11]. The Stability analysis mathematical model is developed in [12]. The stochastic examination of the effect of energy storage systems is described in [13]. Robust fuzzy-sliding model is proposed in [14]. New analytic expression is developed in [15]. In [16], a altered approach for power system TSA is proposed. Adopted CFS is proposed in [17]. TSA with SMES

and GVs is developed in [18], Diakoptics is developed by the authors of [19]. The Wind generator, microturbines, and CHP plants is proposed in [20].

B. *Performance Measures*

This section describes the utilized performance measure from all the reviewed papers. Some performance measures are summarized in Table I. From the table, it is reviewed that the 5% of total contribution have used the CCT estimate difference. 10% of total contribution has used the Frequency measure. 10% of total contributions have used the rotar angle measure. In the total contribution, 15% of contribution have used the active power measure. Subsequently, 20% of total contributions have used the measures like time and voltage. Again, 10% of contributions have used the rotor speed measure. Some other measures have also used by all the authors, and that was the 75% of total contribution.

TABLE I. ANALYSIS ON PERFORMANCE MEASURE

Citation	CCT estimate difference	Frequency	Rotar angle	Active power	Time	Rotor speed	Voltage	Others
[1]	✓							✓
[2]		✓						✓
[3]		✓						✓
[4]			✓					
[5]				✓				✓
[6]					✓			✓

[7]					✓			
[8]					✓			✓
[9]				✓				
[10]						✓		✓
[11]							✓	✓
[12]								✓
[13]								✓
[14]				✓				✓
[15]					✓			✓
[16]							✓	✓
[17]			✓					✓
[18]							✓	✓
[19]								
[20]						✓	✓	

C. *Attained best Measures*

The achieved best measure is given in this section. Table II reviews the achieved best performance measure from the total contributions. The table clears that the best value of load angle is 53 degree. Then, the best rotar angle is 0.5 rad. The best calculation time is 32.8 sec. The best rotor speed is 0.0025p.u. The best total harmonic distortion is 1.84%. The best bus voltage is 1.01 p.u. Then, the best terminal voltage is 1.02 p.u.

TABLE II. ANALYSIS ON PERFORMANCE MEASURE

Measures	Best value
Load angle	53 (Deg)
Rotar angle	0.5 (rad)
Calculation time	32.8 sec
Rotor speed	0.0025 p.u
Total harmonic distortion	1.84%
Percentage improvement	146%
Bus voltage	1.01 p.u
Terminal voltage	1.02 p.u

D. *Analysis on Terminal Voltage*

This section makes a short analysis on terminal voltage. The graph given in Fig 2 shows the contribution of terminal voltage from the reviewed papers. From the graph, it is evident that the 15% of total contribution have had the terminal voltage in the range of 0.01 p.u to 1.00 p.u. Then, the 30% of total contribution have used the terminal voltage that is in the range of (1.04 p.u to 3.0 p.u).

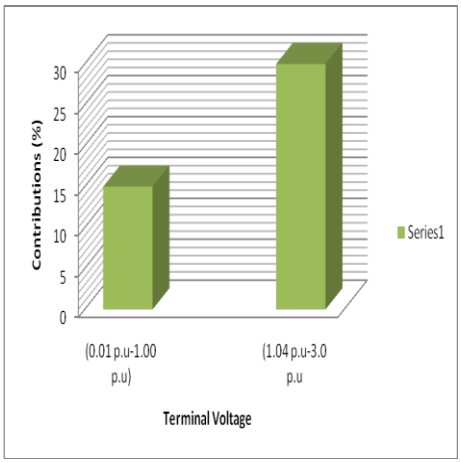

Fig. 2. Analysis on terminal voltage

IV. RESEARCH GAPS AND CHALLENGES

Fault occurrence often leads to instability in the power system or the system device may fall out of synchronism. The study named load flow study must be performed for analyzing the TS of the power system. Still, if the system could not maintain the fault, that might get in stabilize the total system. If the rotor angle oscillation on the last position goes on maximizing and the alterations in angular speed while transient condition maximizes, then the system would not come to its last position. This unbalanced or transient condition directs to instability, in which the power system machines fall out of synchronism. Evaluation of load flow equation via certain methods provides the rotor angle and initial condition as well.

Till date, the computational or evaluation difficulty of TSA issues or problems have set those on being run in real-world applications for supporting the concept of decision making in the trouble time. This unfolding situation view might can help an operator in magnitude considerate of the issues and its consequences so that the proactive metrics might be taken to restrict the incident degree. Moreover, the speedy transient TSA simulation implementations might vitally enhance the reliability of power system that in turns the direct effects like Environmental impact, Electrical usage company profits as well as the satisfaction of customer.

V. CONCLUSION

This paper has comes out with a deep survey on TSA. 20 papers have been reviewed for analyzing the TSA models. Then, the analysis outcomes are given on certain categories such as algorithmic analysis, performance measure and the achieved best measure with respect to figure as well as tabulation. Further, the survey has also given the clear description on challenges and future scope in this TSA problem.

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