Literature Review on Modeling of Integrated T&D System using Dynamic Phasor Technique

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Abstract

With the advent of transitioning from conventional to the modern structure of electrical power systems, the systems are prone to numerous electrical dynamics that no longer have the luxury to be neglected. As a result , the existing time domain simulation software, such as Electromagnetic Transient (EMT) and Root Mean Square (RMS) programs, are becoming inefficient for larger and complex systems. Moreover, the need for integrated Transmission and Distribution (iT&D) research is becoming an obvious trend with more distributed energy resources connecting to the system. The previous researches in this area of modeling and simulation use different techniques but more assumptions and oversimplification have resulted in less accuracy. On the other hand, there is the Dynamic Phasor (DP) concept developed for the analysis of dynamics in power electronics components. With more power electronics components infusing into the power systems, this technique can become a powerful method to analyze the behaviors of the system. Therefore, this literature survey paper extends the idea to implement the DP technique in modeling iT&D systems owing to its multiple advantages over the other methods.

Key Words: *Dynamic Phasor model, EMT program, Integrated T&D, and RMS program.*

1. INTRODUCTION

Electricity is an important resource that constitutes the lifeline of modern society. The primary desire to improve reliability, power quality, and cost reduction makes it indispensable to undergo profound changes in recent years in terms of technology, infrastructures, analysis software, etc. Thus, the electrical power system is becoming exceedingly complex systems ever built by humans. The added components exhibit more non-linear properties due to different switching modes of operations and associated electromagnetic field nature. This would result in abrupt changes in other parts of the system if it is not taken care of appropriately.

For this reason, there is a need to understand the accurate representation of system transients - the main concern of power system engineers - to improve the control and protection strategies using digital signal processing and microcontrollers. Thus, time-domain simulation programs become an integral part of power system simulation tools. It provides a better dynamic response of the power system that can be computed using appropriate mathematical models. The transient phenomena in a power system can be represented in Fig.1.

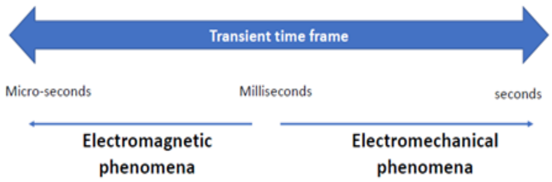

Fig.1: *Time frame of power system transients*

The time range of power system transients varies from microseconds to seconds depending on the nature of the transients. The faster transients that occur from microseconds to milliseconds are called electromagnetic transients and are typically simulated using the Electromagnetic Transients (EMT) program (Dommel, 1969). The other is the Root Mean Square (RMS) program and is used for electromechanical transient simulations. The time frame starts from milliseconds to seconds and uses more approximations to model the system.

These tools were designed and applicable for the conventional structure of power system. However, with the transition to the modern structure of power systems, where more electronic-based components, dynamic loads, and continuous aging of the equipment, are present, there is a drastic increase in stress in the system. To study those dynamics, the existing simulation programs are inadequate. Hence, to overcome this, some researchers and industries are moving towards RMS-EMT co-simulation, also known as hybrid RMS/EMT simulation. The main goal of this new approach is to bring the better of the two approaches together. This enhances the efficiency benefits in RMS simulation for the electromechanical transient phenomena and at the same time give detailed accuracy benefits of EMT simulation for electromagnetic transient phenomena (Hagaman, 2019). Furthermore, the transition is transforming the concept of independent transmission and distribution operations from respective controlling and monitoring centers. Owing to this, a study of merged transmission and distribution system is drawing considerable attention from both industry and academia.

On the other hand, there is a well-established concept of the generalized averaging technique – also known as the dynamic phasor approach – which was proposed by (Sanders et al., 1991b). This technique was initially meant for doing the detailed full time domain representation of power electronics components. So, with the modern power system equipment being mostly electronic-based interfaces, the dynamic phasor approach would be suitable for carrying out the dynamics happening in the system.

Therefore, in this literature review, modeling and simulation of integrated Transmission and Distribution (iT&D) system using the Dynamic Phasor (DP) concept is proposed. It is anticipated to improve and bridge the benefits of both the EMT program and RMS program. Also, this model would act as a better or an alternative method to hybrid RMS/EMT simulation method in analyzing the Power system.

The organization of the remainder of this article is: Background on Conventional power system alongside Modern power system and the modern approach of studies using the dynamic phasor are introduced in Section 2; In Section 3, literature reviews of the previous research along with the drawbacks are presented; The potential solution to fulfilling the modern systems' need and way forward is discussed in Section 4. Finally, the conclusions of this literature review are drawn in Section 5.

2. BACKGROUND

To have a cost-effective and reliable power supply, we need to better understand the nature of the power system's behavior during normal and abnormal conditions. In this regard, electrical power system simulation studies are done before the techniques are commercialized and put to practical applications. It involves power system modeling and network simulation which can be run offline or in real-time.

In this section, the basics of Conventional power system, the trend of modern power systems, and the new approach to studying the transients using the dynamic phasor concept are discussed.

2.1 Conventional Power System

The conventional power system comprises generators, transformers, transmission, distribution, and loads. In this conventional structure of electrical power system, the power flows from big generation plants to load centers via the transmission and distribution system in between. The flow of power is unidirectional. This conventional structure of power system is depicted by Fig.2.

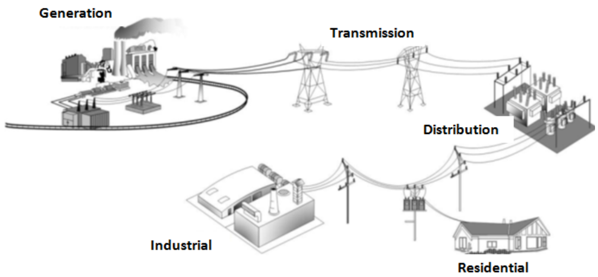

Fig.2: *Conventional power system structure (Wijarn Wangdee, 2017)*

The typical power supply problems to be solved are quality, reliability, and its associated cost. The necessary tools developed for understanding the dynamics involved are EMT program for electromagnetic phenomena and RMS program for electromechanical phenomena.

The EMT program is usually used for the simulation of complex power systems that exhibits non-linear characteristics, especially in the power electronic components and their controllers. Also, the EMT program is meant for analyzing minute detail with great accuracy usually meant for a smaller system. However, the simulation of a large power system using the EMT program is complicated and time-consuming. When the size of the system increases, the modeling method becomes practically impossible given the complexity that arises with the size.

On the other hand, the Root Mean Square (RMS) program is suitable for the bigger system but it compromises the accuracy. Also, it is inadequate to capture the system dynamics in the power system under switching conditions.

The shortcomings and inadequacies of EMT and

RMS analysis tools mentioned above are neither an advantage nor a disadvantage because the methods were programmed to run for a conventional power system.

2.2 Modern Power System

In the modern days, the generation structure becomes bi-directional, which means the customer can become a "prosumer" (an agent that act as both consumer and producer of energy). The electricity generated, using the different types of distributed generations (DG), is injected into the grid when their consumption is less than their generation. Because of that the dynamics produced and pumped into the distribution system and transmission system cannot be neglected. The modern power system network is more complex with various forms of DG, such as Battery Energy Storage Systems (BESS), Plug-in Electric Vehicle, Photovoltaic farms, wind turbine farms, and so on, connected to the system. Even in the transmission and distribution system, more electronic components such as smart devices, inverters, etc. are installed which is becoming the source of various dynamics in the system.
Moreover, with the ever-growing dynamic loads and the continuous aging of equipment, it is augmenting the stress in the electrical power system. This further increases the risk of power quality issues and widespread blackouts. On top of that modern society depends on reliable and economic delivery of power supply.
The typical structure is shown in Fig.3.

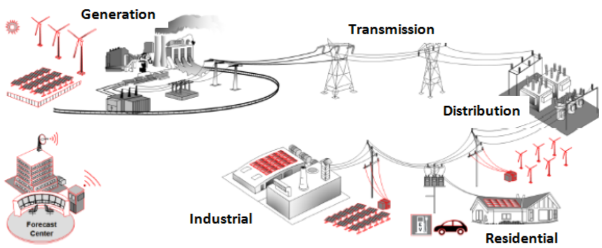

Fig.3: *Modern power system structure (Wijarn Wangdee, 2017)*

Some of the typical characteristics of the modern grid are:

- With the changing trend in electrical power generation, a significant amount of power from a large number of DG units is injected into the distribution system.
- Power may even be transferred from the distribution system to the upstream transmission system resulting in a two-way power flow.
- This paradigm shift leads to the need for redesigning the distributed control and protection systems to handle two-way power flows on distribution and transmission lines.
- A modern T&D system should have the ability to monitor the states of the system and take appropriate action automatically before the outages are spread thus, preventing major system collapses.
- Especially for the distribution system, there are unconventional dynamics due to multiple inverter-based components besides conventional motor loads.
- More and more interactions between the transmission network operators and distribution network operators have to be carried out for smooth evacuation of electrical power.

Given these characteristics, the existing simulation tools become inefficient and insufficient to carry out the dynamics of the system during various conditions. Thus, there is a need to find a middle path approach where the new tool has accuracy greater than the RMS program and simulation time faster than the EMT program.
On the other hand, with more DGs connected into the electrical power system, dynamics from these DGs cannot be neglected. In addition, there is increasing requirement of understanding the interaction between the transmission and distribution system, impacts of smart devices connected in the system, and also the effects due to bidirectional power flows. These result in increase in manual human intervention between transmission and distribution operators as there is a need to coordinate and communicate more frequently. Because of these evolutions and transformations, the concept of independent transmission and distribution operations, from the respective controlling and monitoring centers, are undergoing a major paradigm shift.
These motivations gave birth to the idea of integrated Transmission and Distribution (iT&D) studies. It is a new and emerging research area for simulating the modern power system as there is greater levels of distributed energy resource integration (Jain et al., 2021). This iT&D modeling and simulation technique would provide a better picture of the system dynamics during normal and abnormal conditions.
The existing system models that are mainly used in coming up with these dynamic simulation

programs are:

- Model in a three-phase (ABC) reference frame that uses the EMT program. This frame can represent all the electrical quantities of the electrical system such as currents, voltages, etc. However, due to the presence of AC components, the efficiency of the simulation is affected as the system size increases.
- Model in DQ0 Reference frame that uses RMS program. Due to the slower variation of variables compared to the three-phase ABC reference, the simulation time is faster under balanced conditions. This leads to being more efficient around the system frequency (50 or 60 Hz). But when unbalanced conditions occur in the system or other harmonics, the efficiency decreases drastically.

2.3 Dynamic Phasor

There is an emerging technique of modeling to select only the required frequency components that can exactly represent the anticipated model. This model would be applicable to non-linear models thus, offering definite advantages to model, simulate, and control over other existing time domain simulation tools. The definition and the approach of this dynamic phasor technique are described in detail in this subsection.

The basic idea of the dynamic phasor technique is to approximate a complex time waveform and this time domain periodic waveform $x(\tau)$ can be represented within the interval $\tau\epsilon[\tau - T]$ using a Fourier series of the form:

$$\sum_{k=-\infty}^{\infty} X_k(t)e^{jk\omega_s\tau} \quad (1)$$

Where $\omega_s = 2\pi/T$ and $X_k(t)$ are the complex Fourier coefficients. These coefficients are also called dynamic phasor. These Fourier coefficients are functions of time since the interval under consideration varies with time. The original waveform can have a good approximation when only a few coefficients are provided which can gradually vary with time. This k^{th} coefficient (or k-phasor) is the set of selected Fourier coefficients that provide a better approximation of the original waveform at a time and is determined by the following averaging operation:

$$X_k(t) = \frac{1}{T}\int_{t}^{t-T} X(\tau)e^{-jk\omega_s\tau}d\tau = \langle x\rangle_k(\text{t}) \quad (2)$$

This analysis would provide a dynamic model for the dominant Fourier series coefficients as the window of length varies over the waveforms of interest (Stankovic & Aydin, 2000). The main factor in evolving this dynamic phasor method is the relationship between the derivatives of variable x(τ) and the derivative of the k^{th} Fourier coefficient which is given by the following equation:

$$\frac{dX_k}{dt}(t) = \langle\frac{dx}{d\tau}\rangle_k(\text{t}) - jk\omega_s X_k(\text{t}) \quad (3)$$

By doing the integration by parts and with the use of equations (1) and (2), one can verify this formula. The describing function is beneficial in assessing the k^{th} harmonic of the right-hand side of the time domain mode ⟨(d/dt)x⟩k.

a. Application of Dynamic Phasor

The dynamic phasor was initially developed for the analysis of power electronics components. But gradually, with more power electronics components inbuilt into the power systems, this technique is becoming a powerful method to analyze the behavior of the system. This new technique is proven to have improved the accuracy and speed of the simulation as reflected in (Stankovic & Aydin, 2000), (Stankovic et al., 2002), (Demiray et al., 2008), (Chandrasekar & Gokaraju, 2015), and (Miao et al., 2015). This means the system size to model in the EMT program can be enhanced and at the same time provide more accurate and faster simulation results.

The application of this dynamic phasor technique ranges from analyzing the dynamic simulation in electrical machines, transmission systems, distribution systems (where more and more DGs are connected), and even the integrated T&D system. It can be used for - but not limited to - analyses of power flow, power quality analysis for static VAR compensator, dynamic voltage restorer and STATCOM, analysis of asymmetric faults, symmetric faults, sub-synchronous reactance, and impact of a distributed generation when connected to the distribution grid. It is also being used for modeling power electronics converters, transmission lines, distribution lines, transformers, etc. Further, the dynamic phasor modeling technique has been found to achieve improvement in the efficiency of analysis for

AC/DC distribution systems (Long Cheng et al., 2022).

The dynamic phasor concept can be modeled as another option for Discrete Fourier Transform (DFT). This DFT tool is used in computing the Phasor Measurement Unit (M. G. Siddh & Mahipalsinh C. Chudasama). Besides that, it can also be used for modeling Aircraft Electrical Power Systems (Yang et al., 2013).

b. Advantages of DP over Existing Models

Usually, transient stability programs are used to carry out the dynamic behavior and stability of power systems. The typical conventional time domain models are used in running these programs. But with more DGs and the introduction of power electronics components into the modern power system grid, this approach poses a challenge in understanding the dynamic behavior. Therefore, it requires full-time domain simulation.

One option to make large-scale modeling in electromagnetic transients program is by substantial improvement of storage and computational time. However, this won't be economical with the current technology. Until such barriers are parked, the large-scale power system modeling and simulation using the EMT program would be difficult. Thus, developing the alternative algorithm and technique would be a cheaper and more effective solution.

On the other hand, the full-time domain simulation model also called dynamic phasor is widely used in power electronics-based equipment and proposed in (Mattavelli et al., 1997). Thus, this technique could be implemented in modern power systems too where more and more smart devices and components are added to it.

The academicians and researchers of the past have known that using the dynamic phasor approach, one has to deal with more variables, especially during the modeling of the larger system. Because of it, the number of equations and variables to consider in the phasor dynamics approach is higher than the conventional methods of modeling and simulations of power systems. The number of differential equations too, increases. However, the dynamic phasor technique offers superiority over the conventional models such as models in three-phase (ABC) reference frame (EMT model), models in DQ0 reference frame (RMS model), etc. Some of the notable advantages are:

- The dynamic phasor approach reveals and quantifies dynamical couplings that are not essentially obvious from the beginning of the conventional models.
- The liberty of selecting the variable k in the dynamic phasor model provides wider bandwidth in the frequency domain than the conventional model that is used in RMS programs like simulation tools.
- The dynamic phasor approach tends to vary slowly even when there is an abrupt change in instantaneous quantities. This response is suitable for simulation that is faster than EMT programs.
- The time domain simulations of larger systems with more power electronic-based components result in computational burden besides giving fewer insights on its dynamics. This will indirectly impact the efficient and effective design of protection schemes and controllers. The dynamic phasor approach – on the other hand – gives better information to such analytical issues.
- The DP variables are slow-varying complex quantities under both balanced and unbalanced conditions. This would allow larger time steps during the simulation process.
- The DP approach provides a middle path between the approximations of phasor-based representation and complex conventional time domain EMT program-like simulation.
- The extraction of small-signal characteristics of system studies becomes difficult as the switching models are discontinuous in the conventional models.
- In conventional models, the complex behavior of switching functions of power electronics components makes it complex to develop the models with greater accuracy.
- For unbalanced and faulty regimes, the conventional techniques lose their efficiency and are time consuming due to presence of second harmonic.

3. RELATED WORKS

The literature survey presented in this paper is carried out in two broad areas viz. on dynamic phasor technique and iT&D modeling technique. The details of the respective literature reviews and findings are summarized in the following subsections:

3.1 The Research on iT&D

Relatively few studies and research have been done on iT&D dynamic modeling and simulation, such as (Huang & Vittal, 2017), (Balasubramaniam & Abhyankar, 2017), (Jain et al., 2016), and (Lammert et al., 2017). Some of the techniques used are Mixed Three-Sequence/Three-Phase Modeling, Integrated Grid Modeling System (IGMS), Integrated Transmission and Distribution model, Integrated System Modeling (ISM) approach, etc. However, their primary focus has been using steady-state analysis only. As the system composition changes gradually with migration from the conventional to the modern structure of the power system, the techniques are becoming inefficient. Because of this, iT&D simulation study is turning out to be one of the focus areas of research in recent years.

Some of the notable reasons to consider for iT&D studies with regard to the modern electrical power systems, for secure operation of the system, are:

- An improved understanding of the degrees of connection and interaction between the transmission and distribution networks
- Knowing the system behavior as more and more smart devices are installed with the aim of moving towards smart grids.
- With the increasing number of DG and other distributed energy sources, the number of dynamics injected from these sources into the electrical power systems cannot be ignored even at the transmission system level.
- Frequent changes in generation power supply and fluctuation in the loads make it more unpredictable. Therefore, one must understand the system dynamics generated due to these behaviors and the bidirectional flow of power from the DG source to the main grid.
- With the advancement in technologies, the distribution system level has the prospective to reduce or mitigate its impact on the transmission level. So, integration of T&D studies would offer more understanding of the influence of distribution on the transmission level.
- There is a rapid evolution of the distribution system and thus, there is a need to examine the degree of interaction with the conventional transmission system.

From the literature, a survey carried out and as mentioned above, some of the limitations come across for integrated T&D modeling using the existing approaches are:

- More assumptions and oversimplification of the distribution system provide less accurate simulation results.
- "Modeling and solution complexities are significantly increased compared to modeling transmission systems in positive-sequence or three-sequence" (Huang & Vittal, 2017).
- It is not possible to reuse the current sequence-based modeling at transmission level.
- The modeling of transmission and distribution systems was considered as one single model. This single component modeling does not provide the details of the dynamics happening in the system.

3.2 The Research on the Dynamic Phasor Technique

The concept of the dynamic phasor technique was proposed by (Sanders et al., 1991a) to be used in power electronics-based systems. But with modern power systems infused with more and more power electronics components, this technique could be emulated in studying the system dynamics. Hence, this is one of the emerging research areas that the researchers in the power system field are looking forward to.

In the power system studies, the previous works mainly focused on the subsystem level with the generation system level (Demiray et al., 2008), (Chandrasekar & Gokaraju, 2015), (Xu & Wang, 2007), transmission system level (Stankovic & Aydin, 2000), (Hannan & Chan, 2004), (Anderson et al., 1995), (Sultan et al., 1998), and distribution system level (Miao et al., 2015). The respective modeling and simulation are considered only as an independent system or subsystem. All these results have shown significant improvement in accuracy and simulation time.

The previous studies include – but are not limited to – stability analysis of inverters of micro-grid applications, analysis of unbalanced poly-phase alternating current (ac) machines, impact analysis when DG is connected to the distribution grid, short-circuit analysis of a system, and so on. With the change in the components and structure of the electrical system, the corresponding behavior changes drastically. Therefore, it is required to study the consequences if more components of the system with the generation, transmission, distribution, and loads are to be considered in the overall modeling.

4. POTENTIAL SOLUTION

In the conventional systems, the simulation tools used for transmission and distribution systems are being modeled and analyzed separately. These cause difficulty in analyzing the impacts on transmission as well as distribution systems and their dependencies in detail.

On the other hand, the dynamic phasor technique provides advantages over the other methods. However, the author could not substantially conclude the drawbacks except for a few limitations on existing iT&D modeling techniques from the literature reviews. The literature on these modeling is sparse and on top of that, no studies were found having done using the dynamic phasor.

Therefore, in order to provide better or alternative solutions to the existing methods of modeling and simulations, the modeling of iT&D using the dynamic phasor technique could be explored as a novel and way forward solution. For this research and the way forward solution approach, the power system network considered could be a transmission system connected to a distribution network through a substation transformer. This network would then be mathematically modeled using the dynamic phasor concept in which the transmission network is taken as one subsystem and the distribution system as another subsystem. The linking boundary conditions and assumptions would be considered similar to the modeling of integrated T&D with other modeling techniques mentioned in the previous sections.

The iT&D power flow during normal and abnormal conditions could be the main focus of the research. It would be solved by doing the iterative process of a three-sequence power flow for the transmission network and a three-phase power flow for the distribution level (Huang & Vittal, 2017).

Some important factors to consider while deciding on the model of iT&D systems are:

- The physical features of the transmission network as well as the distribution network.
- The assumptions for common modeling are reasonable for dynamic simulation as well as for power flow.
- Use of prevailing modeling practice for transmission as well as distribution networks.

Although the ideal situation would be modeling and simulation of a bigger and more practical system with the generation, transmission, distribution, loads, and distributed generations, it is almost impossible to model and simulate it. The complexity of the modeling is increased exponentially with more components added to the model. One main challenge anticipated to come up with iT&D simulation model would be the different network representations in the transmission and distribution networks. Since the transmission networks are largely assumed to be balanced, the three-phase network topologies are predominantly built for distribution networks. However, the Multi-Area Thevenin Equivalent (MATE) approach proposed in (Huang & Vittal, 2017) would be utilized in the network solution step to address this challenge.

For modeling of the defined network, MATPOWER simulation software could be used for the transmission network because it assumes the system to be balanced, and GridLAB-D software for the distribution system.

Finally, the simulation results could be benchmarked against the commercially available EMT simulation tools. The commercial programs that are capable to model the three-phase network topologies are Distributed Engineering Workstations (DEW) software, CYME, Electromagnetic Transient Simulation Programs – Revised Version (EMTP-RV), GridLAB-D simulation software, and Alternative Transients Programs (ATP). Alternatively, the results would be compared with previously researched iT&D modeling techniques used as mentioned in the previous sections.

5. CONCLUSION

The modern electrical power system is a blend of electrical and electronic components. The dynamics injected by the electronics components no longer can be neglected either at distribution level or at transmission level. With this evolution, the existing methods of analyzing the dynamic system behaviors, such as the EMT program and RMS program, become inadequate. Therefore, the emerging dynamic phasor technique could be emulated in modern electrical power systems too. It offers several advantages over the conventional EMT and RMS models. The research papers of the past have proven the improvement in accuracy and simulation time, however, on a subsystem level.

Also, on the other hand, the recent trend of the need to have an iT&D power system provides the opportunity to do research in modeling and simulation. But, the existing researches focus on modeling using different techniques. These methods have some shortcomings.

In view of these, this literature survey concludes that the dynamic phasor technique could provide a better or alternative method for modeling and simulating the modern iT&D power system. It would help the power system engineers understand the dynamics injected due to more electronics components used in the power system networks.

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