Integrated Transmission and Distribution Modelling Using Multi-agent Based Framework

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Abstract. Technological changes that enable the widespread adoption of renewable energy-based distributed generation and shift in the source of transportation sectors are introducing nascent challenges and opportunities in power generation, transmission, and distribution systems. Conventionally, the transmission and distribution systems were analyzed in a segregated manner under the assumption that the aggregate load subtended by the distribution systems at the transmission systems would remain constant, but with changing technologies and deployment of large-scale renewable sources of generation along with the increase in electric vehicle charging stations made the load subtended at the transmission level by distribution system to become uncertain with a probability of reverse power-flow. Therefore, an adequate method for analyzing the integrated transmission and distribution systems is to be evolved; in this article, we propose a multi-agent-based system framework for analyzing the integrated transmission and distribution system. The developed framework would be used to analyze the IEEE 9 bus test system at the transmission level and the IEEE 13 Bus test feeder at the distribution level.

Keywords: Integrated transmission and distribution · Multi-agent-based system · Active distribution system

1 Introduction

Conventionally the distribution system has been analyzed separately from the transmission systems, and different tools and methods were employed to investigate the transmission and distribution system [6,7]. The motive behind the segregated analysis of the Transmission System (TS) and Distribution System (DS) was derived from the observations that the aggregate load subtended by the DS at the TS generally happened to be balanced with a slow but predictable variation. This notion regarding the behavior of the DS began to be challenged owing to large-scale changes being implemented at the DS. These changes include changes like the change in the distribution system from a conventionally passive

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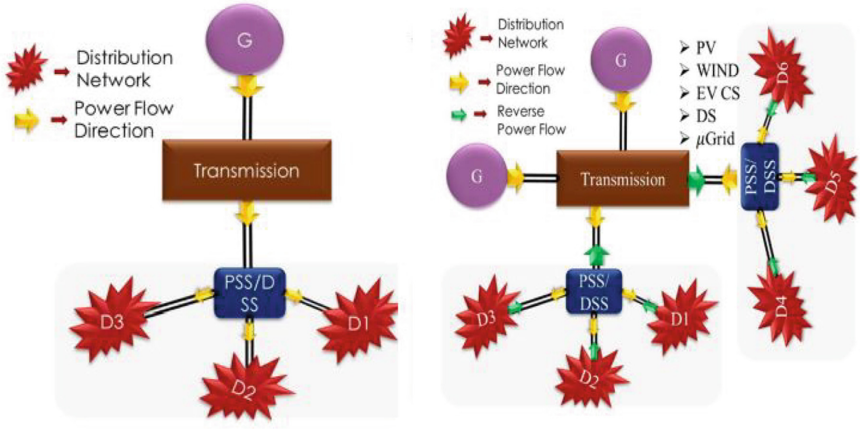
to an active distribution system, and transformation in the transportation sector from fossil fuel-based energy sources to electricity-based energy sources. A passive distribution system is one in which there is a prevalence of consumers (customers can only draw power from the grid). In contrast, in an active distribution system, consumers behave as prosumers injecting power back into the grid. The prosumers generally have localized power generation sources like rooftop PV to meet their needs and feed the excess power back to the grid. The usual DS that used to be unidirectional (i.e., power was fed from the transmission substation to the distribution substation) transformed into a more versatile system with probable backward flow of power from DS to TS. These changes mandate the necessity for having an adequate methodology for integrated analysis of transmission and distribution systems. The changing nature of the Transmission and Distribution ($T\&D$) system is schematically inked in Fig. 1. The Fig. 1(a) illustrates the conventional scenario of TS and DS interaction, and Fig. 1(b) sketches the anticipated transformed behavior of TS and DS interaction in which power flow from DS to TS has also been inked. Methodologies and platforms that could be employed for co-simulation and $T\&D$ systems integrated studies for assessing the impacts of phenomenons happening at DS on TS and vice-versa are being developed. The investigation of economic aspects for the operation of $T\&D$ systems has been performed in [8] through a two-stage optimization-based method. The authors utilized the $T\&D$ economic models based on the residual demand curve and transmission-constrained supply curve. In [9], the global power flow method based on a master-slave splitting mechanism has been presented as a tool for ITD analysis. Authors in [4] propounded architecture for analyzing and monitoring the behavior of integrated $T\&D$ operation with a higher degree of DER penetration at DS levels. Another very interesting approach has been inked in [3], here existing simulators of TS and DS are linked using FCNS (Framework for Network Co-simulation), and the presented methodology could be utilized for analyzing the dynamic behavior of $T\&D$ system. Further, a scalable multi-time scale framework for $T\&D$ analysis using HELICS has been proposed in [1]. Although different tools and techniques are being developed and investigated for integrated analysis of TS and DS, the methodology for analyzing the integrated behavior of TS and DS systems for quasi-static analysis that may be utilized in applications such as ATC/ADC assessment are yet to be developed. In the present article, we would be detailing the formulation of a framework for integrated $T\&D$ studies that would employ a multi-agent-based mechanism.

2 Overview of Multi-agent Based System for Integrated TS and DS Analysis

A computerized system comprising multiple intelligent agents working in unison to solve a common problem is termed a Multi-Agent System (MAS). In our study, we would be promulgating a MAS-based framework for integrated analysis of TS and DS. We would be utilizing two different tools that are typically used for analyzing the transmission and distribution system separately. These tools would be interchanging the information at the ‘PCC’ (point of common coupling) through the multiple agents of MAS. MATPOWER [11] would be used



(a) Conventional transmission and distribution system.

(b) Modern transmission and distribution system

Fig. 1. Changing scenario of transmission and distribution systems.

Table 1. MAS implementation algorithm.

Step	Description
I	Model the TS system in TS solver
II	Identify the load nodes at which the DS are to be connected as ADS_{nodes} (PCC)
III	Assign agents for all the ADS_{nodes}/(PCC) of MAS
IV	Define the operating mode
V	Get the states i.e. (P, Q, V, δ, DS_{losses}, taps, caps)
VI	Establish the data exchange through MAS agent vectors using *agent2tr* protocol

as a TS solver and OPENDSS [2] as DS solver. 'MATLAB' would be used to develop the MAS based framework. The MATPOWER is TS solver developed using 'MATLAB' language while the OPENDSS is an open-source tool developed specifically for distribution system analysis. In the proposed approach we would be utilizing a Component Object Model (COM) based interface for accessing the variables in OPENDSS. The schematic illustration of the proposed framework is shown in Fig. 2, the figure shows two parts, in (a) the solver's organization and COM interface have been inked while part (b) indicates the interaction between TS and DS through agent-based 'COM' interface. Two protocols namely (*agent2tr*/*tr2agent*/*dn2agent*/*agent2dn* protocol) have been used for establishing interaction between TS and DS. Table 1 shows the implementation procedure for the proposed MAS-based mechanism.

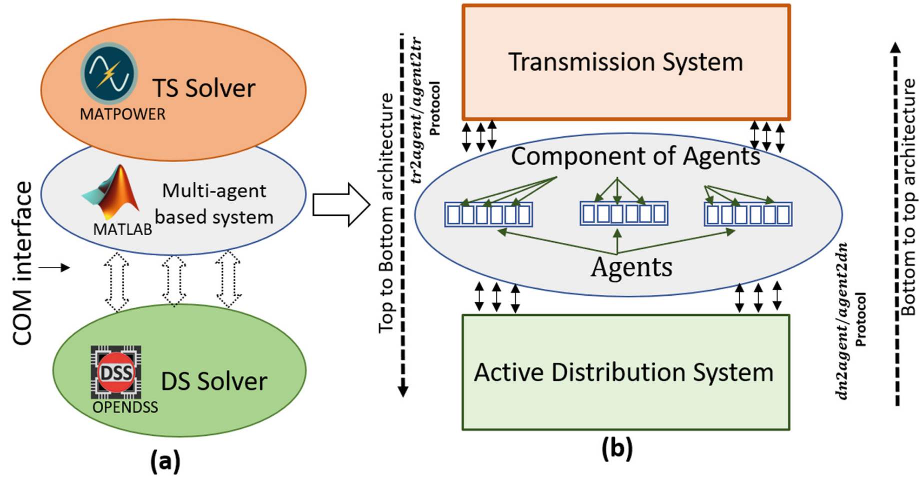


Fig. 2. Schematic illustration of the proposed framework.

The exchange of information between TS and DS is materialized through various agents α of the MAS-based system. The presented framework would work in two different configurations as given:-

- *Top-bottom approach*:- In this configuration, the solution to TS is obtained and it is communicated to the DS.
- *Bottom-up approach*:- Here the DS is solved first and the information is exchanged with TS for carrying out further analysis through the MAS agents.

The cardinality of the agents in the MAS-based system would be equal to the number of ADS_{node} in the system. Each agent would be a vector containing information and the status of different variables and components, for instance, α_i^j denotes the jth in the ith agent. Each agent would be having two major constituents namely TS agent vector and DS agent vector. state present in the DS connected to that ADS_{node}.

$$\alpha_i = \{\alpha_1, \alpha_2, \cdots, \alpha_a\}$$
$$\alpha_i = \{\alpha_i^1, \alpha_i^2, \cdots, \alpha_i^{a_i}\} \quad (1)$$

3 Modelling of the Active Distribution System and Integrated TS and DS System

The conventional DS is transforming into an Active Distribution System (ADS). In ADS, we have a mix of different sources (power producers) and sinks (power consumers) along with prosumers (consumers having to consume, produce and inject power into the grid). The ADS we will model in this work will comprise Solar PV-based distributed generation sources and prosumers. We will consider two types of prosumers; in the first category, it will be assumed that they have off-grid PV installation. In the second category, grid-connected systems with net metering provisions will be considered.

3.1 Solar PV-Based der Modelling

Modeling of the Solar PV has been done by considering it as a PQ load and designating P as $-ve$ for a generation. At the same time, Q would be $+ve$ or $-ve$ based on the operating scenario to which the smart invertor connecting the Solar PV to the grid would be subjected. The β distribution has been considered for modeling the *pdf* of solar irradiance on an hourly basis so as to incorporate the uncertainties associated with the PV power output [5]. The P and Q support that the smart inverter would provide by sourcing the PV module is given by

$$P^{PV} = P - P^{inv}_{losses} \tag{2}$$

$$Q^{inv} \simeq Q \tag{3}$$

$$P^{inv}_{losses} = (1 - \eta_{inv}) \cdot \sqrt{P^2 + Q^2} \tag{4}$$

In the above equation, the η_{inv} is the operating efficiency of the inverter, and the Q^{inv}_{max} is the maximum reactive power support that the inverter could support.

3.2 Prosumer Modeling

In the Indian scenario, consumers with off-grid systems generally use them to meet their power requirements in case of unreliable power supply and lower their power consumption through the grid, reducing their energy costs. To model such behavior of the consumers, we have to consider their contracted load, load profile, and PV power profile.

$$P^i_{og}(t) = P^i_c - P^i_d(t) - Pg^i_{og}(t) \tag{5}$$

The P_{og} would be subjected to the following constraints

$$0 \leq P^i_{og}(t) \leq P_c \tag{6}$$

In the above equations, P^i_{og} is the power demand by the ith prosumers having P_c as its contracted load, P^i_d as its actual demand and Pg^i_{og} be the power produced by the off-grid system at time t. In DS the contracted load refers to the maximum rated demand (in kW, KVA, or HP) agreed to be supplied by the distribution company which the user can draw from the grid [10]. It is general practice that distribution companies penalize the users for violating the contracted load limit. Contrarily, for grid-connected systems installed through net metering schemes in some states of India (like UP), the prosumers could feed back to the grid. Such systems can be modeled using the following equations.

$$P^i_g(t) = P^i_c - P^t_d - Pg^i_g(t) \tag{7}$$

The P_g^i would be subjected to the following constraints

$$-P_{pv}^i \leq Pg_g^i \leq P_{pv}^i \tag{8}$$

In the above equations, P_g^i is the power drawn by the ith grid-connected prosumer, Pg_g^i is the power generated by the PV installation, and P_{pv}^i is the installed capacity of the grid-connected system. The grid-connected systems with net metering or gross metering facilities are being offered in several states of India (like U.P) for loads starting from 1 kW to 2 MW. In such net metering provisions, the distribution companies bill the prosumers in terms of net energy injected into the grid. Such schemes are vital in promoting the large-scale deployment of grid-connected PV systems but in long run, they would limit the development of peer-to-peer energy trade through open access at distribution levels. Therefore, in long run, it can be expected that the new tariff policy would evolve as present tariff policies would not foster open access and competition in the distribution market.

3.3 TS and DS Modelling

The nodes in the TS to which the ADS would be connected are identified. The agents used in the MAS would equal the number of ADS nodes in the TS. The total load at the ADS node at TS level is decomposed into two parts, the first being the ADS node and the second fixed load. The mathematical modeling of the same is given as under

$$ADS_{load} = \zeta Pd^{DS} \tag{9}$$

$$Fixed_{load}^{P}CC = Pd_i^{PCC} - \zeta Pd^{D}S \tag{10}$$

$$\%ADS_{load} = \frac{\sum_{i=1}^{n_c} \zeta Pd_i^{DS}}{\sum_{i=1}^{n_c} Pd_i^{P}CC} \tag{11}$$

The ADS_{load} is the load subtended by the DS at the TS, ζ is number of ADS that form the DS which is connected to PCC, n_c refers to number of ADS nodes present in the system. The schematic illustration of the developed TS and DS integrated system is shown in Fig. 3.

4 Problem Formulation

The integrated TS and DS system has been solved by adhering to the power flow constraints of at both transmission and distribution levels. The power flow equations and constraints are given as under:

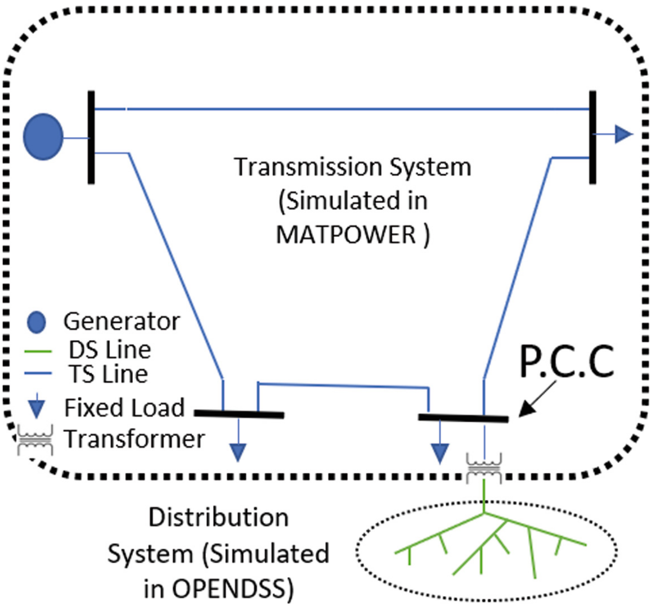


Fig. 3. Integrated TS and DS model.

4.1 TS Level

$$\sum_{i=1}^{Ng} Pg_i - \sum_{i=1}^{Nd} Pd_i - P_{loss} = 0 \tag{12}$$

$$\sum_{i=1}^{Ng} Qg_i - \sum_{i=1}^{Nd} Qd_i - Q_{loss} = 0 \tag{13}$$

$$P_i = \sum_{i=1}^{N} V_i V_j Y_{ij} cos(\theta_{ij} - \delta_i + \delta_j) \tag{14}$$

$$Q_i = \sum_{i=1}^{N} V_i V_j Y_{ij} sin(\theta_{ij} - \delta_i + \delta_j) \tag{15}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{16}$$

$$Pg_i^{min} \leq Pg_i \leq Pg_i^{max} \tag{17}$$

$$Qg_i^{min} \leq Qg_i \leq Qg_i^{max} \tag{18}$$

In the above equations, Ng is the number of generators, Nd is the number of load buses. N is the total number of buses in the TS system under study. Pg_i, Pd_i are active and reactive power generated by ith generator. V_i is voltage at ith bus, Y is the bus admittance matrix, θ_{ij} is the admittance angle of branch connecting bus i to j, and δ is the voltage angle.

DS Level. The ADS has also been solved by adhering to the distribution system power flow equations. These equations are given as under

$$Pd^{DS}(t) = \sum_{i=1}^{N_{pv}} P_i^{PV}(t) + P_i^{og}(t) + P_i^{g}(t) - \sum_{i=1}^{Nl} Pd_i^{DS}(t) \tag{19}$$

$$Qd^{DS}(t) = \sum_{i=1}^{N_{pv}} Q_i^{PV}(t) - \sum_{i=1}^{Nd} Q_i^{DS}(t) \tag{20}$$

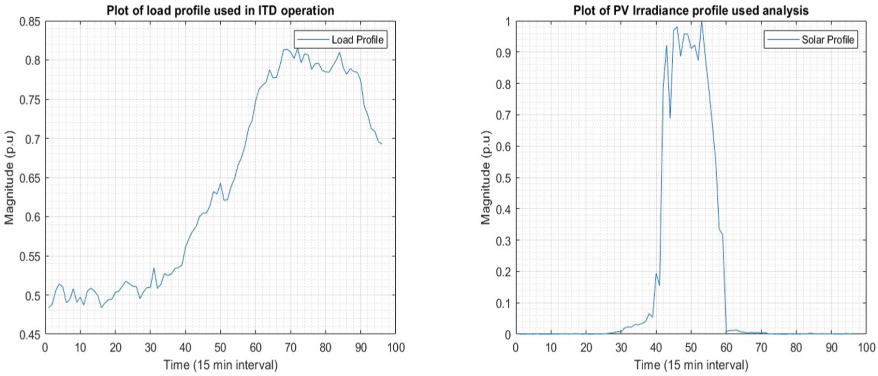
The above equations are to be solved while adhering to the voltage and power flow constraints of the ADS.

5 Case Study

The framework that has been proposed is tested for its efficacy using a modified IEEE 9 bus test system at the transmission level and a modified IEEE 13-node feeder at the distribution level. We would consider bus 7 of the TS system as the PCC to which the ADS would be connected. The details of the modification done are shown in Table 2. The load profile and PV profile used in the simulation for the TS and ADS system is shown in Fig. 4a, and Fig. 4b. The load and PV profile used contains the hourly load variation at an interval of 15 min. The framework proposed in this article has been used to analyze the integrated operation of TS and DS. The total TS active power loss and voltage of the ADS node obtained during the integrated operation have been shown in Fig. 5a and b. The PV power injected by the off-grid rooftop PV and grid-connected rooftop PV has been inked in Fig. 6a and b respectively. From the plots, it can be seen that the power that is drawn/injected by the prosumers into the distribution grid from the roof-top PV systems depends on the type of the roof-top PV installation

Table 2. Description of the test system.

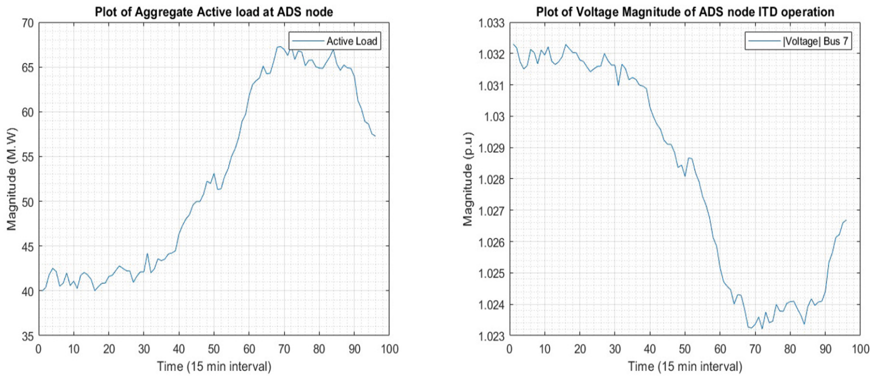
S.N	Modification done in TS				
	Bus No.	Fixed load		ADS load	
		P (MW)	Q (MW)	P (MW)	Q (MW)
1	7	82.67	24.49	17.33	10.51
–	Modification done in DS				
S.No	Grid connected rooftop-PV		Off-grid connected rooftop-PV		
	Bus No.	PV rating	Bus No.	PV rating	Connected load
1	675.1	485	652.1	120	128
2	675.2	68	670.1	15	17
3	675.3	290	670.2	60	66
4	611.3	170	670.3	100	117



(a) Load profile

(b) PV profile

Fig. 4. The hourly load and PV profile for 24 h at 15 min intervals.

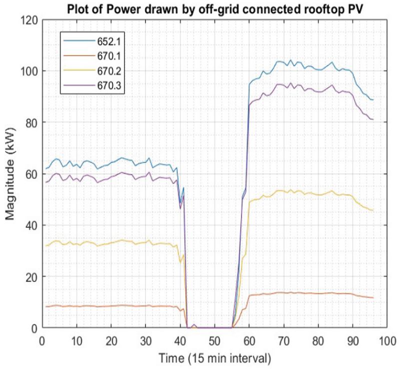


(a) Total Aggregate load at ADS(PCC) node.

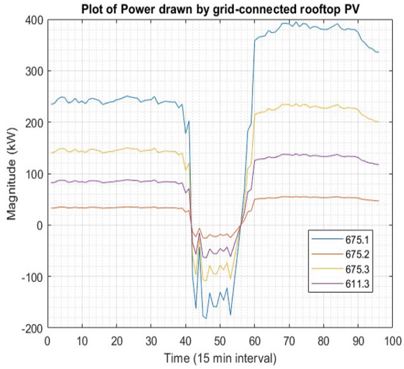
(b) Voltage of ADS (PCC) node

Fig. 5. The hourly active load and voltage magnitude of ADS (PCC) node during 24 h simulation at 15 min intervals.

they have. For instance, in Fig. 6a the minimum power exchanged with the grid is zero because the figure corresponds to off-grid PV system which does not have the provision of injecting power back to the grid. On the contrary, from Fig. 6b it can be seen that the total power drawn by the consumers becomes negative indicating that the power is being fed back from the prosumers to the grid.



(a) Power drawn by consumers with the off-grid rooftop PV system.



(b) Power drawn/injected by consumers with the grid-connected rooftop PV system.

Fig. 6. The power drawn/injected by consumers with rooftop PV systems during 24 h simulations at 15 min intervals.

6 Conclusion and Future Work

The integration of renewable generation sources at the DS level as rooftop PV Systems (prosumers) and independent power producers could cause a probable reversal of power flow from ADS to TS through the PCC. In this article, we have proposed a multi-agent-based framework for the integrated analysis of TS and DS. The proposed method has been tested on a test system comprising a modified IEEE 9 bus system at the TS level and a modified IEEE 13 node feeder at the DS level. The variations in aggregated active load at the ADS node and the power drawn by the prosumers during the hourly simulation for 24 h have been delineated. The future work would be comprised of analyzing the behavior of blockchain-enabled peer-to-peer market operation and the effect of cyber-attack/contingency events on operational, control, and economic aspects of ITD operation.

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