Chapter 6

AGGREGATED EFFECT OF ACTIVE DISTRIBUTION SYSTEM ON AVAILABLE TRANSFER CAPABILITY USING MULTI-AGENT SYSTEM BASED ITD FRAMEWORK

The proliferation of renewable energy sources both at transmission and distribution levels causes uncertainties in the existing system's electrical parameters. It would subsequently affect the assessed available transfer capability for the system. Further, an impending shift in modes of transportation from conventional to electric vehicles also poses a challenge as they would act as a potential source/sink depending upon psycho-economic factors. In Active Distribution Systems (ADS), the distribution system operator employs tools such as Volt-Var optimization to reduce the economics of operation. Attempts to assess the overall effect of the ADS considering the presence of electric vehicles, Volt-Var Optimization on ATC of the system have been investigated in this chapter. A framework for assessing the impact of ADS on the transmission system has been employed to emulate IEEE 24 BUS RTS at transmission-level and IEEE 123 BUS system at the distribution level. Two indices $ATCE_{factor}$ and $ATCVR_{factor}$ have been introduced for assessing the impact of ADS on ATC. It is observed that the presence of distributed energy resources and proper utilization of Volt-Var techniques have the potentials of increasing the ATC of the system.

6.1 INTRODUCTION

Assessing the Available Transfer Capability (ATC) has been an essential task of the Transmission System Operator (TSO) at the Transmission System (TS) level. The growing economic, legal, and environmental concerns may cause some of the transmission corridors to carry more power than their capability. To avoid such a situation, the information pertinent to the ATC of the system becomes vital for the TSO. Methodologies for real-time assessment of ATC have been developed in the recent past. ATC of the system depends on a number of factors such as TS topology, forecasted load, and spatial distribution of generation dispatch profile, weather forecast, etc. Conventionally, the loads have been considered as a fixed PQ load while evaluating the ATC. This assumption would be valid if the decoupling of transmission and distribution is insignificant. With changes being introduced in the operating and regulatory practices of the Distribution System (DS), the traditional philosophy of segregated analysis of Transmission and Distribution (T&D) does not hold good. Thus, a new approach for the integrated analysis of the $T\&D$ system has to be developed [86]. Moreover, the increased penetration of renewable energy sources as Distributed Energy Resource (DER) may affect the behavior of Transmission and Distribution system operation. The increase in decentralized and distributed generation has increased the complexity and inter-dependency of the transmission and distribution system along with the probable occurrence of reverse power flows from distribution systems. Additionally, transformation in the transportation sector resulting from the shift in travel modes from conventional to Electric Vehicles (EV) also poses a challenge as EVs could act as a potential source/sink depending upon psycho-economic factors. The traditional DS is transforming to Active Distribution System (ADS) with Advanced Distribution Management System (ADMS) capabilities whereby Volt-VAR optimization, demand response, DER scheduling, Electric Vehicle to Grid coordination (EV2G) are being monitored, controlled, and managed.

The present chapter begins with the development of a Multi-Agent System (MAS) based framework for integrated analysis of T&D system, followed by a pattern search based optimization method for assessing the ATC while considering the presence of ADS. The main contributions of this chapter are as follows:

- Multi-Agent System based software-in loop scheme for integrated monitoring and analysis of system whereby $MATPOWER$ and $OPENDSS$ software are used for modeling T&D.
- Development of methodology for impact assessment of ADS on ATC of the system.
- Assessing the effect of deploying Volt-VAR optimization (CVR) in ADS on ATC of the system.
- Impact assessment of presence and absence of $DERS$ (PV, WIND, PV & WIND) in ADS at DS on ATC of the system at TS have been analyzed.
- Two indices, namely $ATCE_{factor}$ (ATC Enrichment factor) and $ATCVR_{factor}$ (ATC CVR factor) have been proposed to assess the overall aggregated effect of ADS on ATC.

6.2 MAS BASED ITD FRAMEWORK

MAS based integrated transmission, and distribution framework has been developed using the Component Object Model (COM) interface between the MATLAB and the $OPENDSS$ software. The MATLAB acts as the master while utilizing the $OPENDSS$ as a slave during software in loop simulations to materialize the functioning of the ITD platform. The ITD platform employs an agent-based communication between the T&D system. The TSO, build and modeled in master, performs the transmission system analysis, control, and monitoring function while being in continuous coordination with the energy management system. Analogously the DSO performs the functions of distribution system analysis (modeled in slave). ITD interaction starts with the identification of nodes/buses/substations acting as $p.c.c$ (point of common coupling) for the T&D interface at the boundary of TS and DS. The number of agents required for setting up the ITD framework is equal to the number of $p.c.c$. Different components of the ITD platform are discussed hereunder: -

6.2.1 $pcc\ Node$

The buses/nodes at which the ADS load is connected has been considered as pcc node. The pcc node could be taken as a floating bus because there happens to be a range of operating points at which the states of pcc node may exist [95]. Depending on the network conditions and the states of the floating bus, it could be set as PV or PQ_{bus} . If the pcc has sufficient reactive power capability to control the node voltage then it would be considered as PV bus within the capability range; otherwise, it would be taken as PQ_{bus}.

6.2.2 Multi-Agent based System

The interaction between $T\&D$ has been performed by using a multi-agent-based system. The architecture of the MAS system has been shown in Figure 6.1. The MAS consists of several agents $\mathcal{A}$ which are employed for exchanging the information between the DSO and the TSO. The proposed MAS system can function in two different modes: -

6.2.2.1 *Top-Bottom mode (t2b):*

In this mode, the states of active distribution nodes are evaluated at the TS level and then communicated to the DS level through the MAS.

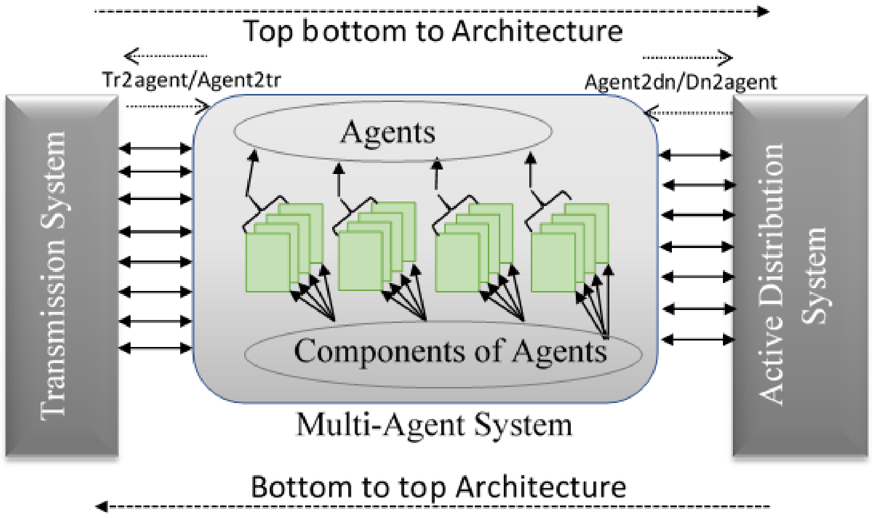


Figure 6.1 MAS ITD framework

6.2.2.2 *Bottom-top mode (b2t):*

Here, the DSO first estimates the states of the ADS at the active distribution nodes and communicates to the TS level through MAS.

The cardinality of agents in the MAS would be equal to the number of active distribution nodes considered. An agent $\mathcal{A}_i^j$ represents j^{th} state of i^{th} agent, each agent has a TSO agent vector and DSO agent vector as two major components. These vectors would be decisive for TSO/DSO side variables, depending upon the architecture being employed. The formation and composition of the agent vector have been given in equations. (6.1) to (6.3).

$$\mathcal{A} = \{\mathcal{A}_1, \mathcal{A}_2 \dots, \mathcal{A}_{na}\} \qquad 6.1$$
$$\mathcal{A}_i = \{\mathcal{A}_i^1, \mathcal{A}_i^2, \dots \mathcal{A}_i^{na_i}\}$$

$$\mathcal{A}gent(\mathcal{A}) \Rightarrow \mathcal{A}gentware(TS, \mathcal{A}gent, mode)$$
$$agentware|_1 \Rightarrow agent = tr2\mathcal{A}gent(TS) \quad \forall t2b \qquad 6.2$$
$$dn2\mathcal{A}gent(DS)$$

$$\mathcal{A}gentware|_2 \Rightarrow \mathcal{A}gent = \mathcal{A}gent2tr(TS, \mathcal{A}gent) \quad \forall t2b \qquad 6.3$$
$$\mathcal{A}gent2dn(DS, \mathcal{A}gent)$$

Here, n is the number of agents na_i is the number of component of i^{th} agent. In $\mathcal{A}gentware|_{mode}$ (subroutine to $tr2\mathcal{A}gent/dn2\mathcal{A}gent$ or $\mathcal{A}gent2tr/\mathcal{A}gent2dn$ protocol) the mode (1 or 2) determines whether the $tr2\mathcal{A}gent$, $dn2\mathcal{A}gent$, $\mathcal{A}gent2tr$, or $\mathcal{A}gent2dn$ protocol would be invoked. The input parameters for $\mathcal{A}gentware$ are transmission network information (TS), agent (initially a set of a null matrix), mode. The mode whose value is 1 or 2 determines whether the information is commuted from transmission/distribution interface to agents or from agents to transmission/distribution interface, respectively. The agent $\mathcal{A}_i$ contains the information pertinent to the TS node i, PQ flexibility region of i^{th} interface, state variables at the i^{th} interface in the purview of ADS.

6.2.3 Interface Architecture

The ITD interface can be achieved by adopting any of top to bottom or bottom to top topology. In the bottom to top topology, the ADS demands and DERs determine the interface parameters through the DSO, while in the top to bottom architecture, the interface parameters are governed through the TSO. The flexibility of controlling the ADS resources either by issuing controls either from TSO or DSO through a coordinated mechanism could be enabled for enhancing the functioning of the overall system.

6.2.4 System components modeling

6.2.4.1 *ITD System Modelling*

The impact of ADS on $T\&D$ will not be visible if the percentage of load present in the ADS is not of considerable amount. In order to ensure the presence of adequate ADS load (ADS_{load}), the conventional fixed PQ load considered at TS has been decomposed into two parts, i.e., i) Fixed PQ load and ii.) ADS_{load} . In literature, different methods for bus splitting have been proposed, such as [164], which could be utilized for expansion and inclusion of the ADS at the pcc. A generalized representation of an ITD system has been shown in Figure 6.2, where the ITD boundary, fixed load, and ADS_{load} at two pcc distinct nodes have been illustrated. The ADS_{load} at pcc of ITD boundary is formed by clusters of Active distribution feeders. The number of feeders connected at the pcc is assumed to be a function of the percentage of ADS_{load} present at the ITD boundary. Computation of ATC is usually performed for transmission corridors connecting two different areas of the system (source to sink). For analyzing the significant effect of ADS on ATC, the fixed loads in the sink area of the transmission system are equivalently represented by the combination of fixed PQ load and ADS_{load}. The $\%ADS_{load}$ in the sink area can be obtained as: -

$$ADS = \pi P d^{DS_i} \tag{6.4}$$

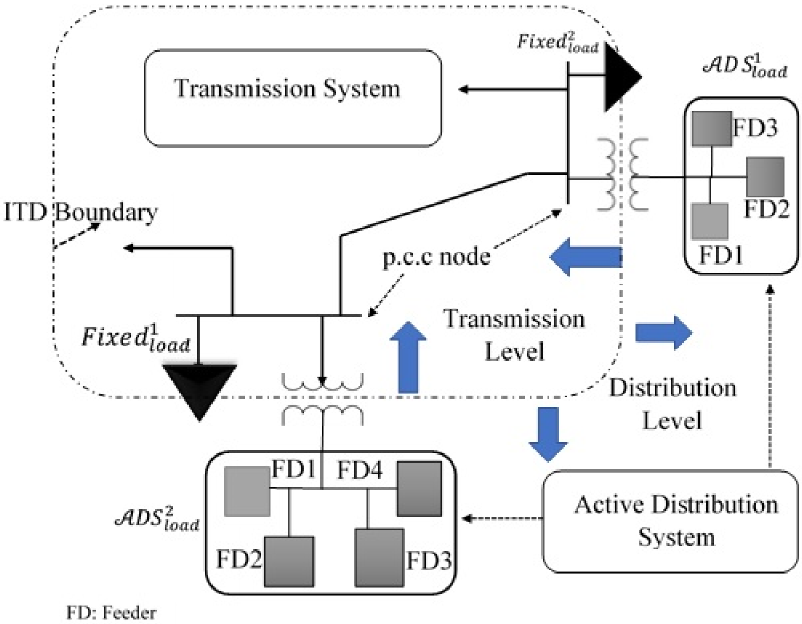


Figure 6.2 Schematic representation of aggregated ITD System

$$Fixed_{load}^{pcc,i} = Pd^{pcc,i} - \tau Pd^{DS,i} \qquad 6.5$$

$$\%ADN_{load} = \frac{\sum_{i=1}^{n_{sink}} \tau Pd^{DS,i}}{\sum_{i=1}^{n_{sink}} Pd^{pcc,i}} \qquad 6.6$$

Here τ represents the number of active distribution feeders comprising the ADS_{load}^{i} and $Pd^{DS,i}$ represents the net load demand at DS connected to i^{th} pcc node. The ADS comprise of several DERs such as PV DER, WIND DER, PV&WIND DER, distribution storage (DS), Volt-VAR control schemes (CVR), vehicle to grid EV schemes. The analysis presented in this work considers the impact of the presence of these components on the total load of the ADS and its subsequent impact on the ATC of the system at the TS level.

6.2.5 ADS Component Modelling

6.2.5.1 *DER'S and FACTS Modelling*

The modeling DER'S (i.e., PV and Wind) and FACTS devices (namely SVC and TCSC) have already been discussed in the previous chapters and could be found in Chapter 2 section 2.5.1.

6.2.5.2 *EV Modelling:*

The behavior of EV has been modeled by an agent-based approach whereby the number of EV agents has been taken equal to the number of EV vehicles in the test system under consideration. Each EV agent has different components that are SoC (State of Charge), ρ (probability of requesting connection from CS (Charging Station)), ` (location of agent), v_{id} (vehicle identity).

$$\rho_i = 100 \times SoC_i - \eta_{sk} \times sin\left(\frac{2\pi}{100} \times SoC_i\right) \qquad 6.7$$

Each vehicle is allotted a vehicle id, which would identify the make of the vehicle (i.e., the type of vehicle to which it belongs). It is assumed that the EV owner can readily communicate with the DSO/TSO regarding the information pertinent to the current location of the vehicle, SoC of the vehicle, and the duration of stay for charging. The DSO/TSO, in return, will assign the nearest available charging stations to the vehicle and the price of charging. The net power drawn or injected by the EV is governed by (14)

$$E^{EV,i} = P_t^{EV,i} \times (t_{start} - t_{stop}) \quad 6.8$$

$$E^{EV,i} = \begin{cases} c_t^{r,i} & if\ charging \\ -d_t^{r,i} & if\ discharging \end{cases} \quad 6.9$$

where, $E^{EV,i}$ is the energy absorbed/injected at power $P_t^{EV,i}$, with charging $c_t^{r,i}$ or discharging $d_t^{r,i}$ rate of i^{th} EV at time instant t while t_{start} and t_{stop} are the starting and stopping time of duration during which the EV is connected to the grid through EVSE. The EV which has been allowed to sell power to the grid by discharging rate d^r until and unless the SoC of the vehicle is more than 20%. In order to prevent the vehicle's battery from getting into deep-discharge, the EV is disconnected when the decreasing SoC approaches 20% i.e.

$$\begin{aligned} &if\ SoC^{EV,dis} \leq 20\ \% \\ &disconnectEV \\ &end \end{aligned} \quad 6.10$$

6.2.5.3 *Micro-Grid Modelling:*

Operators of micro-grid hold the flexibility and capability of importing or exporting the active and reactive power from the distribution network through the tie lines connecting them to the distribution systems. The power $P_t^{MG,i}$ and $Q_t^{MG,i}$ injected/drawn by the i^{th} the microgrid at time t is limited by the tie-line capacity [165].

$$P_{t,in}^{MG,i} \leq P_t^{MG,i} \leq P_{t,max}^{MG,i} \; ; \; \forall \, i \in MG; \forall \, t \qquad 6.11$$

$$Q_{t,min}^{MG,i} \leq Q_t^{MG,i} \leq Q_{t,max}^{MG,i} \; ; \; \forall \, i \in MG; \forall \, t \qquad 6.12$$

$$(P_{t,max}^{MG,i})^2 + (Q_{t,max}^{MG,i})^2 \leq \left(S_t^{MG,i}\right)^2, \forall \, i \in MG, \forall \, t \qquad 6.13$$

6.3 PROBLEM FORMULATION

The problem of assessing the effect of deploying the Volt-VAR technique through CVR in ADS on the ATC of the system can be formulated as a multi-level optimization problem. The contingency analysis and ATC assessment are done at the TS level, while Volt-VAR Optimization (VV0) is performed at the DS level. The overall problem of ATC assessment imbibing the uncertainties and complexities of ADS can be expressed as: -

$$\begin{aligned}
& Min(Max\, f(Pd^{TS}, \mathcal{A}_{Pd}^{DS}, \mathcal{C}, B_{SVC}, X_{TCSCS}, cb, tap) \\
& f_{ck}(\cdot) \Rightarrow \{f_{c1}, f_{c2}, \ldots f_{ck}\} \; \{I \; \forall \, k : c_k \in \mathcal{C} \\
& f_{\mathcal{C}_k}(\cdot) = \left. \begin{pmatrix} \displaystyle\sum_{i=1}^{N_{sink}} \left(Pd_t^{TS,i} - Pd0_t^{TS,i}\right)|_{i\in TS} \quad \{II \\ + \\ \displaystyle\sum_{i=1}^{N_{ADS}} (\mathcal{A}_{Pd,i}^{DS,i} - \mathcal{A}_{Pd0_t}^{DS,i})|_{i\in ADS} \quad \{III \end{pmatrix} \right|_{C_k; k\in[1,n_c]}
\end{aligned} \qquad 6.14$$

The equation (26) comprises:- a) control parameters (B_{SVC}; X_{TCSC}; tap and cb), b) independent parameters Pd^{TS};ADS_{Pd}^{DS}, and c) stochastic parameter $\mathcal{C}$. The objective function comprises of three parts (I; II and III as inked in equation (26)) at two different levels (TS & DS) the description of these parts is given hereunder.Transmission Level: ATC

6.3.1.1 *RTCA: stage-I (part I):*

The set of credible contingencies $\mathcal{C}$ has been obtained by Real-Time Contingency Analysis (RTCA) in the quasi-static domain of interest for the considered problem. $\mathcal{C}$ has been identified as a stochastic parameter as it would depend on the various conditions prevailing in the TS. The RTCA identifies the set of critical contingencies, adversely affecting the reliability and performance of the power system [137], [69]. RTCA algorithm does not enforce any time constraint as the computing process does not involve any optimization. Here in this chapter, we have used RTCA developed using $MATPOWER$ also discussed in Chapter 2 section 2.5.4.3, equation (2.58) is applied for contingency ranking as used in [163].

$$\mathcal{C} = \mathcal{J}_{k=1}^{nC_k}(PI_{\mathcal{C}_k}) \quad 6.15$$

$$PI_c = \left[\sum_i \left(\frac{d_{v,i}^u}{g_{v,i}^u}\right)^{2n} + \sum_i \left(\frac{d_{v,i}^l}{g_{v,i}^l}\right)^{2n} + \sum_i \left(\frac{d_{pi,}}{g_{p,i}}\right)^{2n}\right] \quad 6.16$$

In the above equations PI_c is the contingency index, $d_{v,i}^u$; $d_{v,i}^l$; $g_{v,i}^u$; $g_{v,i}^l$ are the normalized upper and lower limit violations for the alarm and security limits, d_j^p, and g_j^p are the normalized power flow limits, n is the normalization factor. The n is exponent used in hyper ellipse equation [163] and is taken as 2. The composite security index (2.58) is used for obtaining the contingency ranking. $\mathcal{J}(\cdot)$ is a function that sorts the PI_c in descending order and forms s set of $\mathcal{C}_k$ credible contingencies with cardinality n_c. The contingency with the highest index being most severe and the one with least value of the index being least severe.

6.3.1.2 *ATC Assessment and Enhancement Problem Formulation: - stage-II:*

Part II of (6.14) represents the basic ATC assessment problem $Max\ \sum_{i=1}^{N} Pd^i - Pd0^i)$. The maximization problem of basic ATC assessment has been impeded by the limiting values of the operational constraints of power system variables. The ATC in the system is affected by the presence of FACTS devices in the system. The ATC assessment formulation considering the impact of FACTS devices and considering the set of credible contingencies is given by

$$\left.\begin{aligned} &Min\left(Maxf(Pd, \mathcal{C}, B_{SVC}, X_{TCSC})\right) \\ &f(\cdot) \Rightarrow \{f_{c1}, f_{c2}, \dots, f_{ck}\}\ \forall\ k : c_k\ \mathcal{C} \\ &f_{ck} = \sum_{i=1}^{N} (Pd_t^{TS,i} - Pd0_t^{TS,i}) \end{aligned}\right\} \quad 6.17$$

Here, $Pd_t^{TS,i}$, and $Pd0_t^{TS,i}$ represents power demand and initial power demand in TS of i^{th} bus at time t for all $k = 1$ to n_c (number of credible contingencies considered from RTCA output). The optimization is achieved while adhering to the impediments of power flow equalities and inequalities. The $Min(Max)$ optimization strives to obtain the ATC value for different credible contingency scenarios provided by the RTCA stage. This is done because the ATC corresponding to the contingency that would yield the minimum value of ATC has to be considered as the final value. If the system is scheduled considering minimum ATC and any other credible contingency happens then, the system would be able to operate reliably and securely. Contrarily, if a higher value of ATC is scheduled and the contingency corresponding to the minimum value of ATC happens, then the system won't be able to satisfy its operational commitments.

6.3.1.3 *Distribution Level: CVR control in ADS*

Volt-VAR optimization in ADS has been achieved by deploying CVR control in the ADS. The motive of using CVR is to operate the ADS at the lower permissible limits of feeder voltages, and such an operation would result in lowering the overall demand of the ADS. The objective function used for obtaining the control settings for CVR deployment is nothing but the total load subtended by the ADS at the pcc of the T&D network and is given along with its constraints in the following subsections.

6.3.1.3.(i) Objective Function

$$\mathcal{A}_{Pd,t}^{DS} = min \left\{ \begin{array}{c} \sum_{i=1}^{nW} P_t^{W,i} + \sum_{i=1}^{nPV} P_t^{PV,i} + \sum_{i=1}^{MG} P_t^{MG,i} + \sum_{i=1}^{nEV} P_t^{EV,i} \\ - \sum_{i=1}^{ld} P_t^{L,i} - P_{loss,total}^{ADS} \end{array} \right\} \quad 6.18$$

Here

$$P_{loss,total}^{ADS} = \sum_{f=1}^{F} P_{loss,t}^{DS,f} \quad 6.19$$

where $f = i \rightarrow j$, $P_{loss,t}^{DS,f}$ is the loss in feeder f of DS at time t, $P_t^{W,i}$, $P_t^{PV,i}$, $P_t^{EV,i}$, $P_t^{MG,i}$ are power exchanged by ith Wind, PV, EV, MG into the ADS at time t, while nW, nPV , nEV, and nMG are the number of WIND, PV, EV, and MG considered in the ADS.

6.3.1.3.(ii) Constraints:

The line flow limits (feeder), voltage limits (nodes), maximum and minimum taps tap (OLTC) and capacitor bank cb settings along with active and reactive power limits of individual DER's/MG along with deep discharge limit of EV s are the impediments by adhering to which the solution of the objective function is obtained.

6.3.1.4 *OPTIMIZATION TECHNIQUE*

The optimization technique discussed in Chapter 2 section 2.4.3 has been used for obtaining the solution of the ITD objective function.

6.3.2 IMPLEMENTATION OF THE PROPOSED METHOD

The method can be implemented using the algorithm shown in Table 6.1. After initialization, when the TS/DS data has been imported, and $Ybus$ along with the $p.c.c$ information have been archived/formulated. The agents which are used for the integrated transmission and distribution co-simulation (shown with their components in figure Figure 6.3) are created. Agents are shown in Figure 6.3(a) contains the initial basic information commuted to DS and TS at time t during the solution process for solving the combined ITD objective function. The problem has been solved under different modes for various cases. These modes and cases are represented in binary form as a component of a flag set k given at Step 13 of the algorithm.

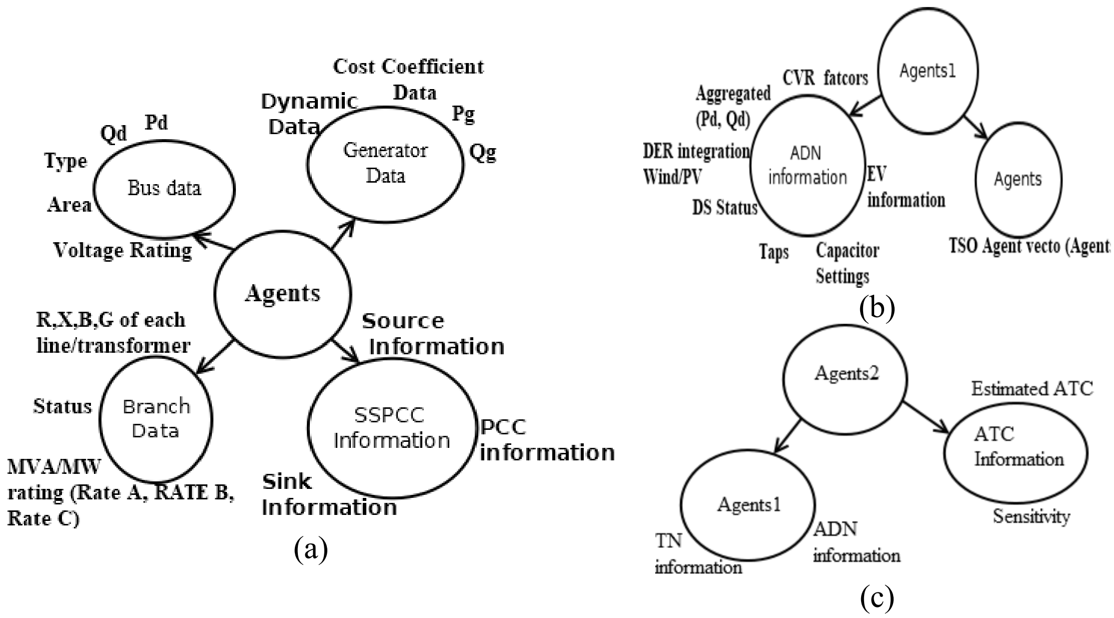


Figure 6.3 Taxonomy of Agents Vectors

The pseudo-code, given at step 14 of the algorithm, has been employed to solve the problem of assessing the ADS impact on ATC. After the solution is achieved, the algorithm acquires the information pertaining to ATC values, DER statistics, the impact of the increase in DER penetration, and the effect of increasing $\%ADS_{load}$ on ATC.

Table 6.1 Implementation Algorithm

<table>
<tr><th>Step</th><th>Comments</th></tr>
<tr><td>Step 1</td><td>Initialize the program.</td></tr>
<tr><td>Step 2</td><td>Import Transmission Network Data (N/W Topology)</td></tr>
<tr><td>Step 3</td><td>Formulate $Ybus$.</td></tr>
<tr><td>Step 4</td><td>Import Source Sink Information</td></tr>
<tr><td>Step 5</td><td>Import Estimated/forecasted load / generation dispatch profile.</td></tr>
<tr><td>Step 6</td><td>Import pcc node information.</td></tr>
<tr><td>Step 7</td><td>Run agent ware program to initialize agent vectors.</td></tr>
<tr><td>Step 8</td><td>Initialize mode of operation
➢ Without CVR
➢ With CVR</td></tr>
<tr><td>Step 9</td><td>Acquire DS information.</td></tr>
<tr><td>Step 10</td><td>Formulate Admittance matrices</td></tr>
<tr><td>Step 11</td><td>Import DER / Cap bank / Tap information</td></tr>
<tr><td>Step 12</td><td>Import estimated/forecasted/generated dispatch and load profile.</td></tr>
<tr><td>Step 13</td><td>Formulate flag k
<table>
<tr><th>K →</th><th>CVR</th><th>PV</th><th>$WIND$</th><th>EV</th><th>$Micro\text{-}GRID$</th><th>DS</th></tr>
<tr><td>Absence</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Presence</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
</table></td></tr>
<tr><td>Step 14</td><td>Pseudo-Code:
$for\ i = 1 : n$ [$n\ different\ cases\ have\ been\ analyzed\ and\ reported\ in\ this\ work$]
$for\ j = 1 : 24$ [$simulating\ for\ whole\ day\ at\ hourly\ resolution$]
$Agents1(iter): agents = DSOcontroller(agents;\ k;\ mult)$
$Agents2(iter): agents = TSOcontroller(agents1;\ mode;\ ck)$
$iter = iter + 1;$
End
End</td></tr>
<tr><td>Step 15</td><td>Acquire the final values of ATC.</td></tr>
<tr><td>Step 16</td><td>Acquire the DER integrations statistics.</td></tr>
<tr><td>Step 17</td><td>Acquire CVR factors.</td></tr>
<tr><td>Step 18</td><td>Acquire the impact of the increase in DER penetration on ATC.</td></tr>
<tr><td>Step 19</td><td>Acquire the impact of an increase in the percentage of ADS and its impact on ATC/CVR.</td></tr>
</table>

6.3.2.1 *Functional description of Agents and their Major Components*

The information carried by the agents could be categorized into two categories i.) Static Information (SI) and ii.) Dynamic Information (DI). SI refers to data that remains constant over time and solution process, whereas DI is that information that keeps on changing with time as the solution progress. The various agents and subroutines used are described hereunder: -

6.3.2.1.(i) Agents vector (shown in Figure 6.3(a)) is created during the initialization and data preprocessing stage. The major components are: -

- Generator data: - Here, SI includes generator cost coefficient (conventional generators), minimum/ maximum generation limits, and dynamic data, while DI incorporates the active cum reactive power generated, generation voltage, and angle.
- $BusData$: - This component contains the information in the form of P; Q; V; δ (i.e., active, reactive power, voltage magnitude, and angle) as DI of different buses/nodes.
- $Branch\ Data$: - Information pertaining to resistance (R), reactance (X), susceptance (B), conductance (G), maximum line flow limits are present as SI while the taps for the on-load tap changers (OLTC) and status of the lines as DI.
- $SSPC\ information$: - The SSPC component hosts source, sink area, and pcc information as DI.

6.3.2.1.(ii) $Agens1$: -

The MAS communicates with the ADS and obtains the states of the different pcc to form this $Agents1$ (as shown in Figure 6.3(b)) vector by appending the relevant information to the $Agents$ vector. Therefore, the components of this vector are the $Agents$ vector and $ADS\ information$. $ADS\ information$ comprises of $CVR_{factors}$, net active/reactive (Pd, Qd) power demand at the active distribution nodes, EVSE information, capacitor bank settings, tap Settings, and $Micro\text{-}Grid$ net withdrawal/injection of net power as DI.

6.3.2.1.(iii) $Agents2$: -

This vector inked in Figure 6.3(c), communicates the information to the TSO so as to facilitate the overall combined operation of $T\&D$ systems. The components of this vector are formed by appending $Agents1$ vector and $ATC\ information$. $ATC\ information$ comprises of the sensitivities and estimated ATC values.

6.3.2.2 *Subroutines of TSO and DSO*

The schematic representation of MAS interaction with TSO and DSO through $Agentware$ has been shown in

Figure 6.4. The taxonomy of subroutines employed by the TSO and DSO for carrying out the optimal operation is explained in subsequent texts: -

- TSO controller contains subroutines for RTCA, PS optimizer for ATC, and Power System Network Solver (PSN); these subroutines are employed by the TSO controller, as and when required to perform the ITD analysis.

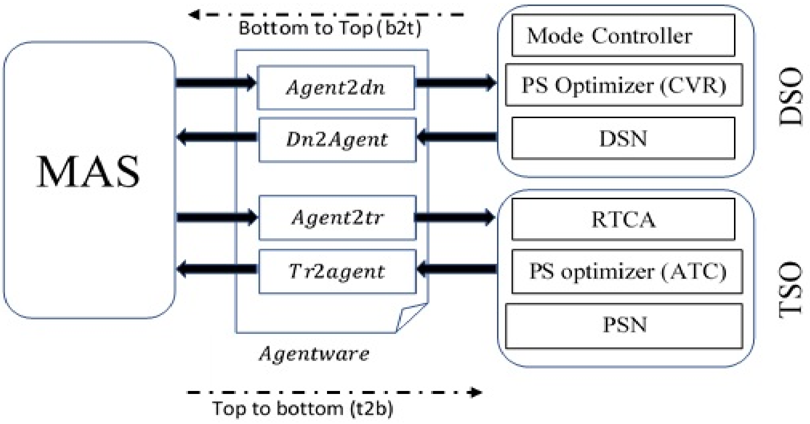


Figure 6.4 TSO and DSO interaction via MAS through $Agentware$.

- DSO controllers inculcate mode control for the subroutines like DER, EV, Capacitor Bank, Transformer Tap control, Micro-Grid, and PS optimizer for CVR along with the Distribution System Solver (DSN). These subroutines are invoked by the DS0 controller depending upon flag k during the solution process.

A flowchart describing the entire process has been shown in figure Figure 6.5. From the flow chart, it could be observed that after the process is started, the transmission system data is acquired. The TS data would be containing information about network topology, generator, and load buses. In the next step, the source/sink area and pcc information is acquired followed by the formation of the agent vectors. Now, counters case 'ca' and time instant 't' are set to zero. For every case, the analyses have been done for the time duration under consideration. The flag 'k' is set to indicate the case which is being studied according to the binary strings shown in Table 6.2. At every time instant, the TS scenario is acquired. This information is sent to the MAS block, where different subroutines are invoked to perform the ITD analysis.

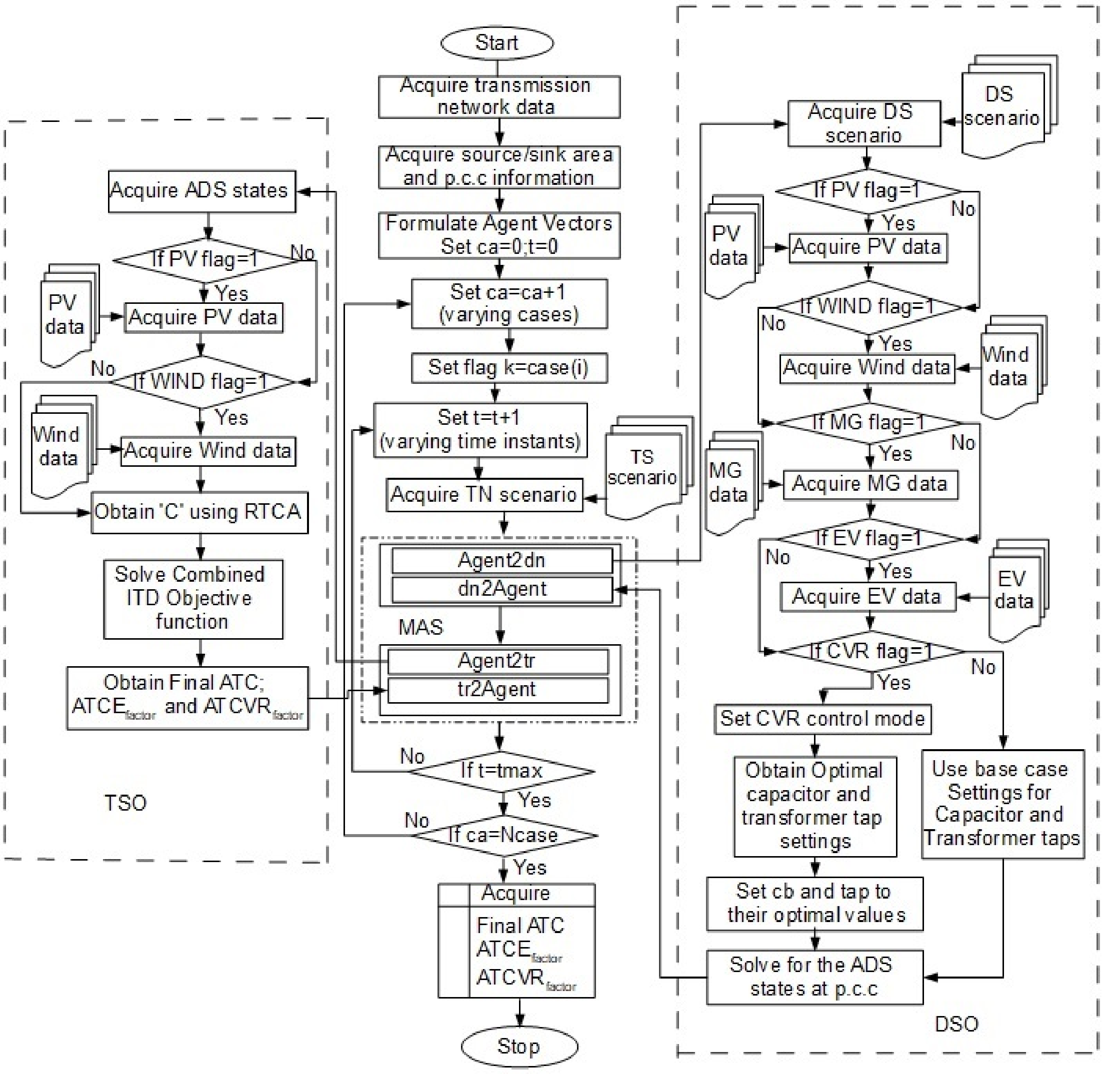


Figure 6.5 Flowchart of the solution process

For $b2t$ approach, the MAS at first uses the acquired information to communicate with the DS controller through the $Agent2dn$ protocol and acquire the states of the ADS using the $dn2Agent$ protocol. In the DS controller, at first, the DS scenario is acquired. After this, the data of PV, Wind, MG, or EV is acquired depending upon the flag k. If CVR is to be considered (i.e., if CVR component of flag k is unity), then CVR control mode would be invoked, and the optimal settings of capacitor banks along with the transformer taps would be obtained by solving the objective function given in (6.18). Once the optimal settings are obtained, the ADS is solved with these settings, and the ADS states at pcc

are communicated to the MAS. If CVR is not to be taken into account, then the base case settings are used, and states of the ADS so obtained at the pcc are sent to the MAS.

Table 6.2 Test cases that have been analyzed.

S. N	Case	CVR	PV	WIND	MG	EV	Description
1	1	0	0	0	0	0	Base Case No CVR
2		1	0	0	0	0	Base Case CVR
3	2	0	1	0	0	0	PV No CVR
4		1	1	0	0	0	PV CVR
5	3	0	0	1	0	0	Wind No CVR
6		1	0	1	0	0	Wind CVR
7	4	0	1	1	0	0	PV Wind No CVR
8		1	1	1	0	0	PV Wind CVR
9	5	0	0	0	1	0	Micro Grid No CVR
10		1	0	0	1	0	Micro Grid CVR
11	6	0	1	0	1	0	PV Micro Grid No CVR
12		1	1	0	1	0	PV Micro Grid CVR
13	7	0	0	1	1	0	Wind Micro Grid No CVR
14		1	0	1	1	0	Wind Micro Grid CVR
15	8	0	1	1	1	0	PV Wind Micro Grid No CVR
16		1	1	1	1	0	PV Wind Micro Grid CVR
17	9	0	0	0	0	1	EV No CVR
18		1	0	0	0	1	EV CVR
19	10	0	1	0	0	1	PV EV No CVR
20		1	1	0	0	1	PV EV CVR
21	11	0	0	1	0	1	Wind EV No CVR
22		1	0	1	0	1	Wind EV CVR
23	12	0	1	1	0	1	PV Wind EV No CVR
24		1	1	1	0	1	PV Wind EV CVR
25	13	0	0	0	1	1	MG EV No CVR
26		1	0	0	1	1	MG EV CVR
27	14	0	1	0	1	1	PV MG EV No CVR
28		1	1	0	1	1	PV MG EV CVR
29	15	0	0	1	1	1	Wind MG EV No CVR
30		1	0	1	1	1	Wind MG EV CVR
31	16	0	1	1	1	1	PV Wind MG EV No CVR
32		1	1	1	1	1	PV Wind MG EV CVR

Now, the MAS sends this information to the TS controller, where the PV data and Wind data (being integrated at TS level) are acquired depending upon the flag k. Using RTCA, the set of credible contingencies C is obtained, followed by obtaining the solution to the combined ITD problem using the PS optimization technique. The final ATC value, $ATCE_{factor}$ and $ATCVR_{factor}$ are obtained. This information is sent to the MAS through the $tr2Agent$ protocol. In the end, when every case has been analyzed, the ATC values and indices ($ATCE_{factor}$ and $ATCVR_{factor}$) are archived, and the process is stopped.

6.4 PROPOSED INDICES FOR IMPACT ASSESSMENT OF ADS ON ATC

Analyzing the impact of aggregated ADS on the ATC of the system requires appropriate indices to be defined. Therefore, two metrics, namely '$ATCE_{factor}$' and '$ATCVR_{factor}$ proposed in this chapter has been delineated as under: -

6.4.1 $ATCE_{factor}$

ATC enrichment factor may be defined as the normalized net enrichment in ATC value achieved on account of incorporating the ADS. This factor can be mathematically expressed as: -

$$ATCE_{factor} = \frac{ATC_{ADS} - ATC_{NoADS}}{ATC_{NoADS}} \quad 6.20$$

The $ATCE_{factor}$ could be positive, negative or zero, a positive value of $ATCE_{factor}$ indicates that the effect of considering the ADS is such that it causes an increase in the ATC value, a negative value indicates a decrement in the ATC, and zero reflects that there is no significant effect of considering the ADS on ATC of the system for the power transaction under consideration.

6.4.2 $ATCVR_{factor}$

The $ATCVR_{factor}$ can be defined mathematically as: -

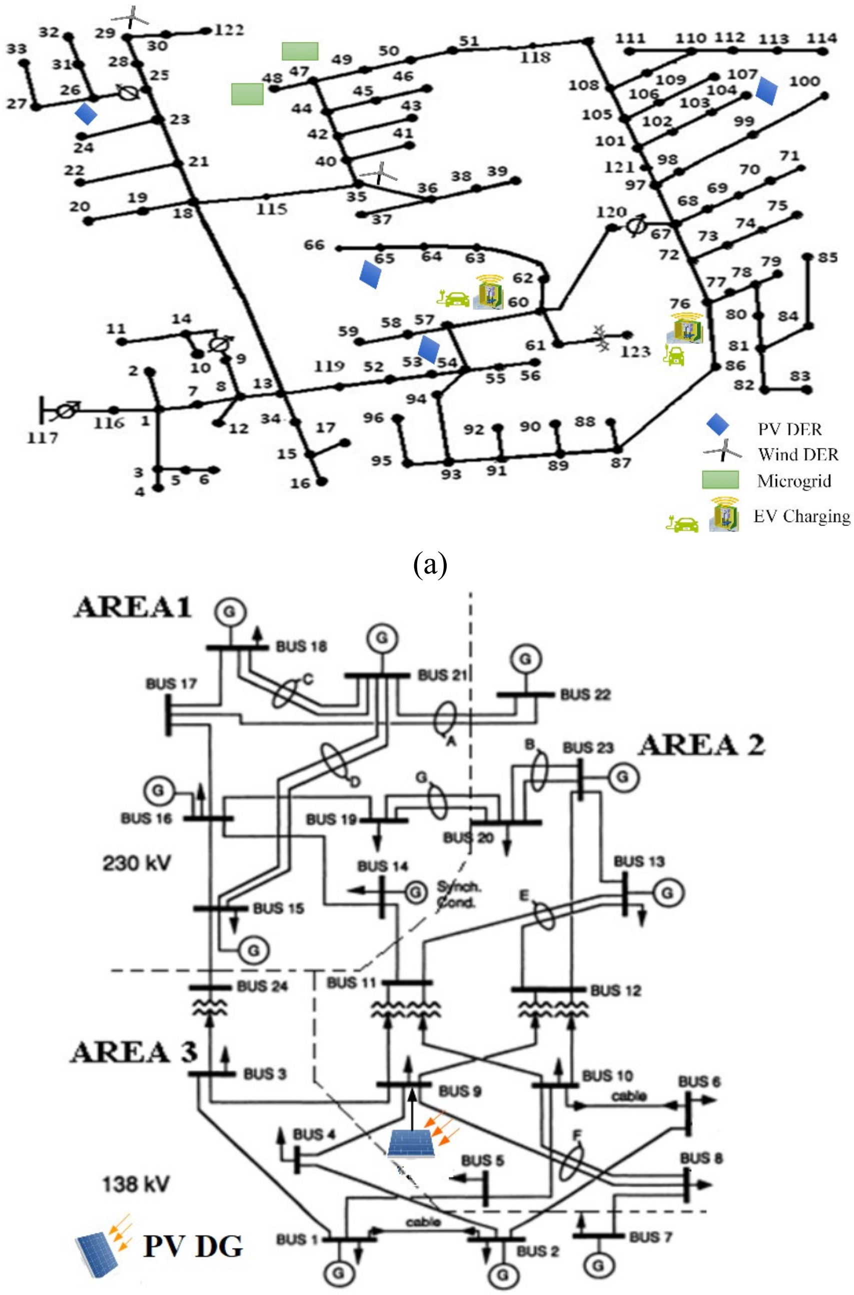
$$ATCVR_{factor} = \frac{ATC_{CVR} - ATC_{NoCVR}}{ATC_{NoCVR}} \qquad 6.21$$

$ATCVR_{factor}$ basically, it indicates the effect of deploying VVO through CVR on the overall ATC of the system for considered power transactions. Its positive value implies that employing CVR has resulted in increment of ATC; negative entails that the CVR control results in the decrement of ATC, and zero instantiates that the VVO through CVR does not affect the ATC substantially.

6.5 RESULT AND DISCUSSION

6.5.1 Test System

Assessment of the aggregated effect of ADS on system ATC has been performed by taking modified IEEE 24 BUS RTS and IEEE 123 bus distribution systems at transmission and distribution levels, respectively. The detailed description of the IEEE 24 Bus system shown in Figure 6.6(b) could be found in [160]. The Modified IEEE 123 bus test system has been shown in Figure 6.6(a), followed by its details in Table 6.3. The aggregated effect of the presence of ADS and its different components have been assessed on ATC for transactions from Area1 to Area2 of the Transmission System. The loads in the sink area (Area 2) have been replaced by a combination of fixed load and ADS_{load}.



(a)

(b)

Figure 6.6 Single line representation of the considered test systems.

The ADS_{load} has been formed by using the clusters of modified IEEE 123 bus distribution network. The analysis has been performed for a large number of possible scenarios, and ATC for transactions from Area 1 to Area 2 has been evaluated.

Table 6.3 Description of DS components

S. N	Equipment	Rating	Location	Power Factor
1	WIND DER	500 kW	29	1
2	WIND DER	600 kW	35	1
3	PV DER	100 kVA	104	0.95 to 1
4	PV DER	400 kVA	26	0.95 to 1
5	PV DER	400 kVA	65	0.95 to 1
6	PV DER	400 kVA	53	0.95 to 1
7	Micro-Grid	130 kVA	47	0.8137
8	Micro-Grid	260 kVA	48	0.8137
9	EV Charging	200 kW	60	
10	EV Charging	200 kW	76	

The effect of presence/absence of different elements of ADS along with the increase in the percentage of ADS_{load} have been the prime focus of the investigation.

6.5.2 Results

The plot of ATC at different $\%ADS_{load}$ over the duration of one day (i.e., 24 hr at a resolution of 15 min $(24 \times 4 = 96)$) have been shown in Figure 6.7. The ATC on the z-axis, $\%ADS_{load}$ on x-axis and duration on y-axis have been depicted. The various test cases for which the impact of ADS on ATC have been analyzed has been given in Table 6.2. The figures Figure 6.7 (a), (b), (e), and (f) shows the case 13, 14, 15 and 16 respectively. Whereas the figures Figure 6.7 (c), (d), (g), and (h) displays the change in ATC from $NoCVR$ to CVR case. It can be observed that due to the consideration of ADS aggregation, the surface of ATC shifts in the upward direction (i.e., towards higher values of ATC).

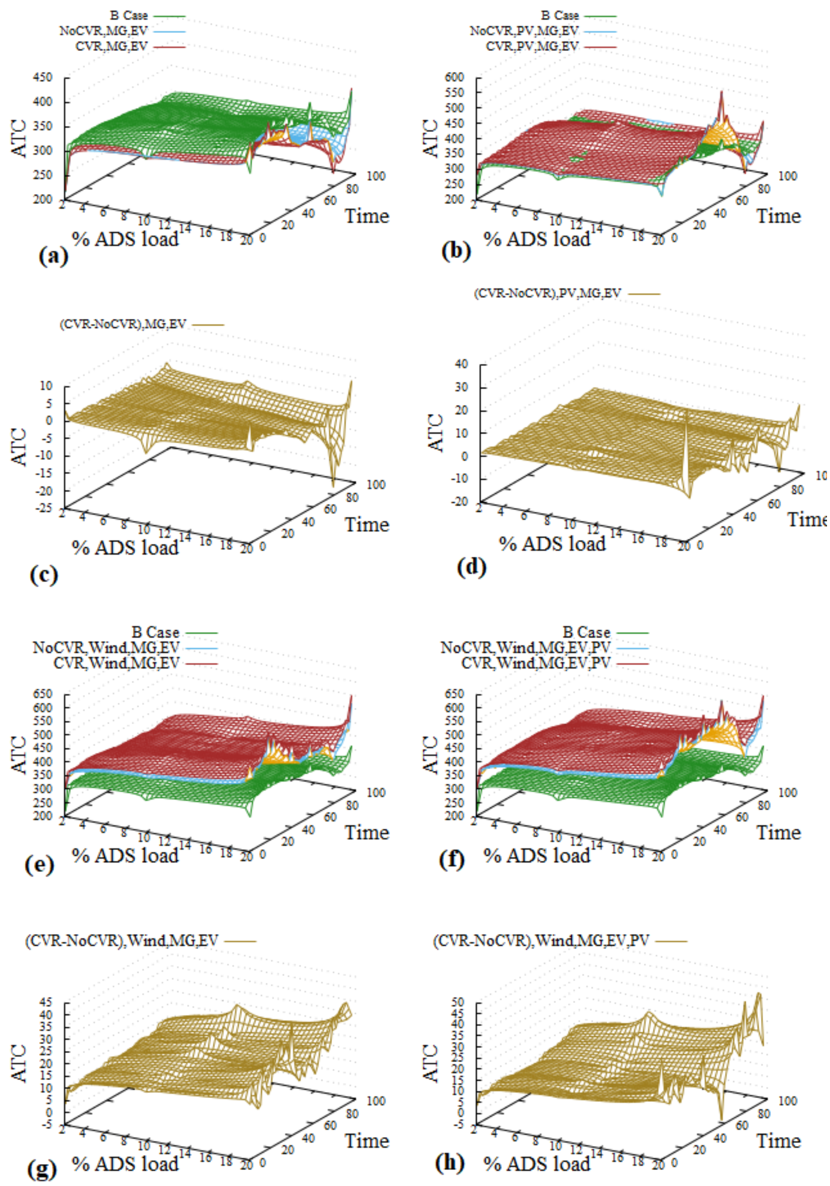


Figure 6.7 Surface plot of ATC for 24 hours at a resolution of 15 minutes.

This shift in the surface is inclined with respect to XY-plane as ATC value obtained ameliorates at higher values of $\%ADS_{load}$. All the cases illustrated in Table 6.2 have been analyzed. The results of the ATC values obtained have been illustrated in Figure 6.8 through the box plot. The ATC values lying outside the box represent the outliers; their presence can be attributed to a variety of factors with uncertainties on account of DERs, EV, and MG contributing the most.

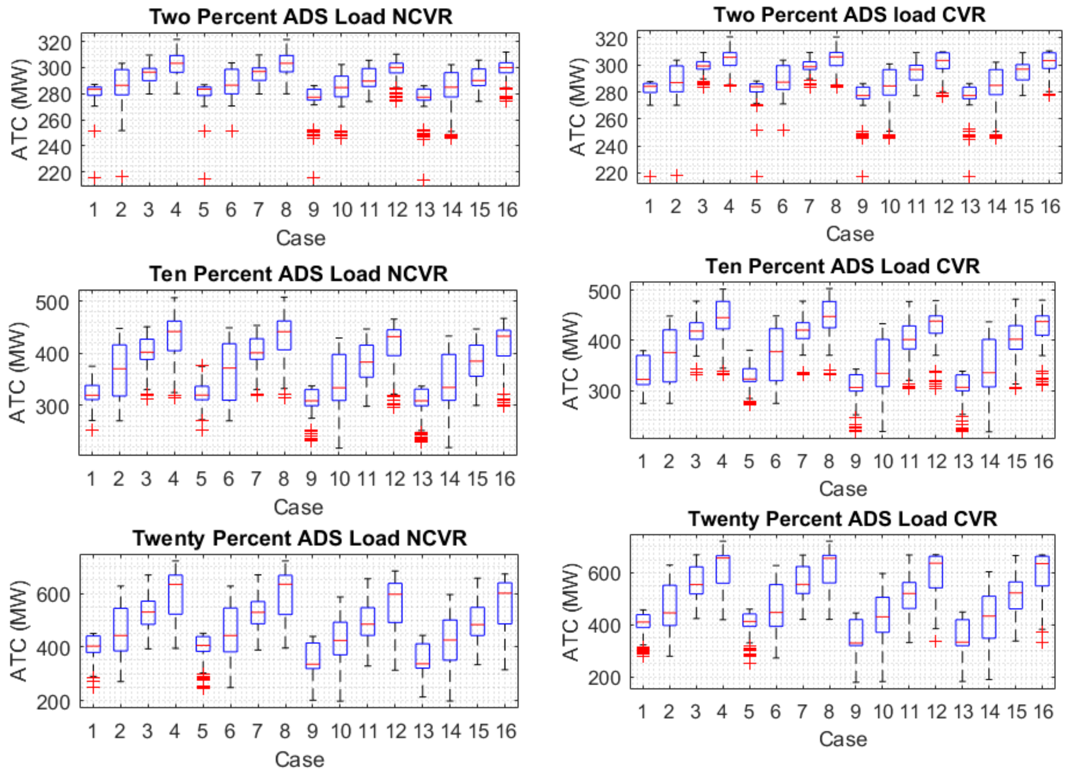


Figure 6.8 Box-plot of ATC at different %ADS_{load} loading for various cases.

Deploying Volt-VAR optimization techniques at ADS have an aggregated effect of overall increasing the system's ATC, as shown in Figure 6.10. It can also be observed that the impact of considering CVR becomes more prevalent at higher %ADS_{load}. Further, the bar graph displaying the minimum, mean and maximum values of ATC at 2%, 10%, and 20% %ADS_{load} for both with CVR and without CVR (NoCVR) case have been inked in Figure 6.10. It can be visualized that for cases (9,10), and (13,14), the minimum ATC under CVR is smaller than the minimum ATC under $NoCVR$ at higher %ADS_{load} (i.e. 10% and 20%), which is not the case for lower %ADS_{load} (2%). These decrements in ATC may be attributed to the consideration of EV and MG in these cases. The $ATCVR_{factor}$ and $ATCE_{factor}$ have been shown in Figure 6.11(a) and Figure

6.11(b), respectively. It can be seen from Figure 6.11(a) that the $ATCVR_{factor}$ can be both positive and negative.

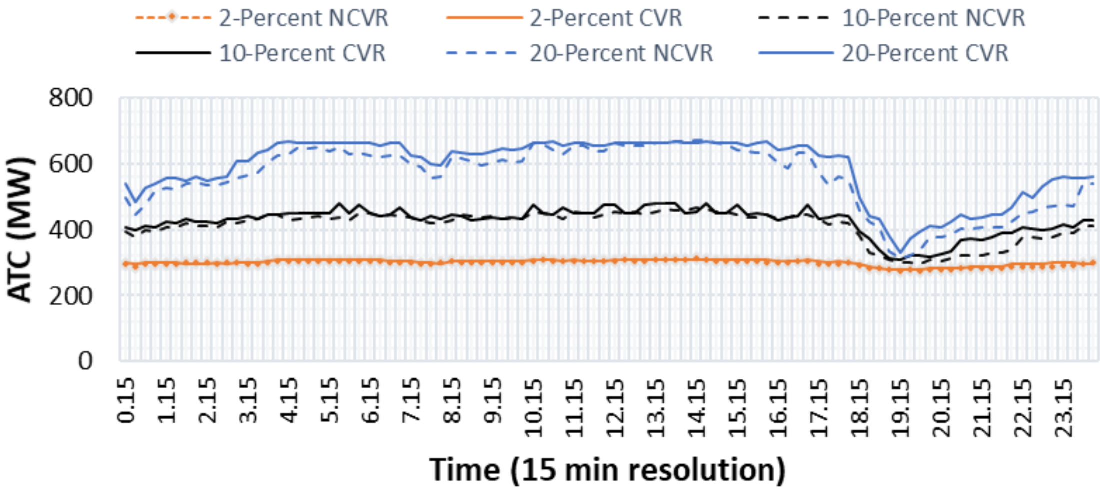
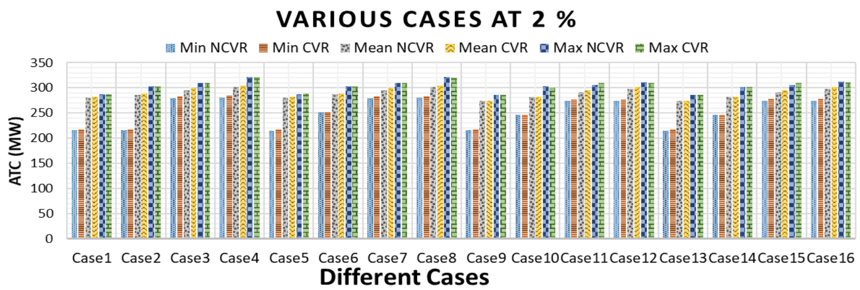
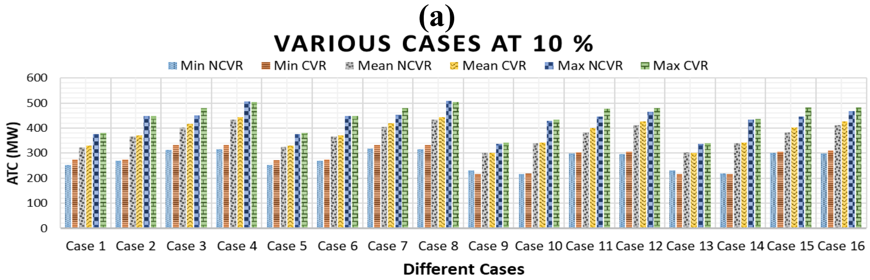


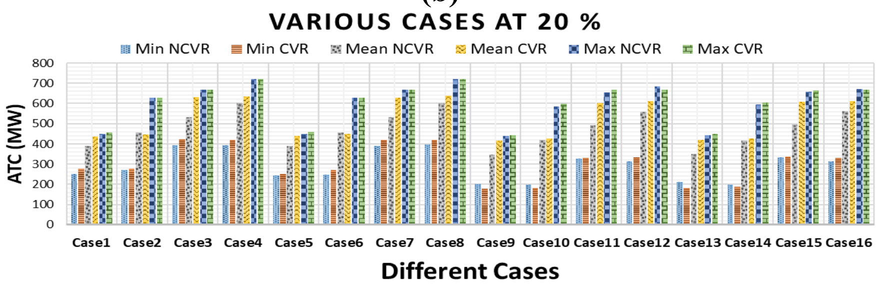
Figure 6.9 Variation of ATC throughout the day for different %ADS_{load}.



(a)

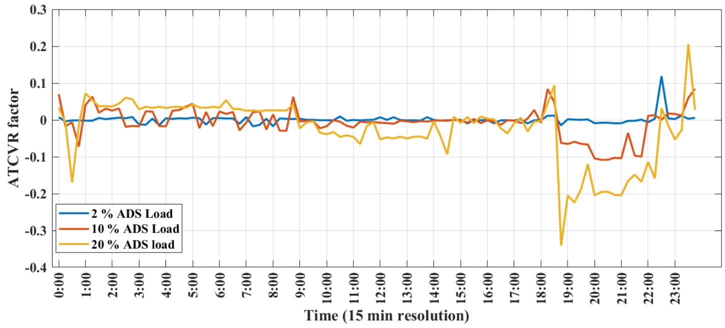


(b)

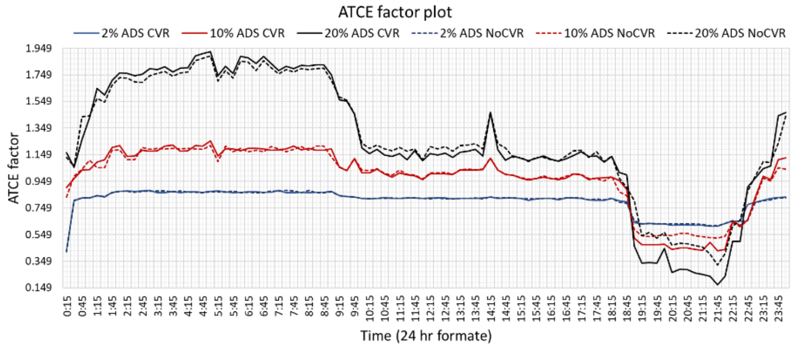


(c)

Figure 6.10 Minimum, Mean and Maximum values of the ATC for various cases at (a) 2 %ADS_{load} (b) 10 %ADS_{load} and (c) 20 %ADS_{load}.



(e) $ATCR_{factor}$



(f) $ATCE_{factor}$

Figure 6.11 $ATCVR_{factor}$ and $ATCE_{factor}$ plots for 24 hours.

The negative value of $ATCVR_{factor}$ indicates that deploying CVR results in reduction of ATC. It can also be observed that magnitude of $ATCVR_{factor}$ increases with increase in $\%ADS_{load}$. From $ATCE_{factor}$ of Figure 6.11(b) it could be manifested that the ATC enrichment varies throughout the day and increases with increase in $\%ADS_{load}$.

6.5.3 Inferences

From the previous section's observations, it can be inferred that as the distribution system becomes more and more active with control and generation (renewable sources) capabilities, the phenomenon at TS would be significantly affected. In terms of impact on ATC, it can be manifested that inculcation of Volt-VAR techniques, MG, DER's, or EV would have a significant aggregated effect on ATC of the overall system. The information pertinent to ATC would be critical for improving the operational condition and the resiliency of the modern grid. Further, the following major inferences could be drawn from the analysis of the considered test system.

1. The impact of ADS on ATC is such that it ameliorates with the increase in the $\%ADS_{load}$. The increment in $\%ADS_{load}$ results in increasing the flexibility of the load projected at pcc, which depends on the operating conditions of the distribution system.
2. The presence of DERs affects the ATC depending upon the nature of DER source. In this work, two different sources of DER's (i.e., PV &Wind) have been considered.
    a. PV-DER:-It can be seen from the plots in Figure 6.7(a), Figure 6.7(b) and Figure 6.7(e), Figure 6.7(h) that the ATC of the system increase during the day (i.e., 28(7:00 am)-68 (5:00 pm) due to presence of solar irradiance) which can be observed from the shift in ATC surface.
    b. Wind DER: - The presence of wind DER results in a reduction of net load projected at pcc (sink area) of the power system as the ADS loads get locally supplied by the wind DER. The change in ATC can be visualized by an upward shift in ATC's surface plot in Figure 6.7(e)and Figure 6.7(f).
3. The effect of micro-grid considered to be present in the ADS as one of its components results in a small decrease/increase in ATC value depending on the power exchanged by the micro-grid with the ADS. The effect is small as the micro-grid considered in this work is assumed to be self-sufficient and draws/injects the power to ADS depending upon its requirements, which is limited by $\pm P_i^{max}$ and $\pm\ Q_i^{max}$ of the micro-grid grid. The effect of micro-grid can be seen from the plots of Figure 6.7(a) and case 7 of Figure 6.10.

4. The effect of the shift in the mode of transportation from conventional to electric vehicles would also affect the net power drawn by the ADS, which in turn impacts the ATC of the system. The aggregated effect of the presence of EV in ADS on ATC has been shown in Figure 6.7(a) and case 9& case 14 of Figure 6.10. The surface plot of ATC shifts below that of the B Case (Base Case) and reduction in ATC values because of consideration of EV due to the installation of EVSE for EV charging.
5. The effect of deploying the Volt VAR optimization in ADS has been shown in the plots of Figure 6.9 and Figure 6.10. It can be observed that the magnitude of change in ATC increases with $\%ADS_{load}$ along with the uncertainties (which can be attributed to the uncertain and intermittent nature of sources of DER's and load at EV Charging Station).
6. The $ATCE_{factor}$ basically indicates the aggregated effect of considering the ADS on the ATC of the system. Higher the $ATCE_{factor}$ the higher is the impact of ADS on ATC at the transmission level. The $ATCE_{factor}$ would be varying with the time of day, day of the week, and month of the year. Similarly, the $ATCVR_{factor}$ indicates the impact of deploying Volt-VAR control in ADS through CVR on the ATC of the system. The higher the value of the $ATCVR_{factor}$, the higher would be the effect of deploying CVR in ADS on ATC of the system.

6.6 CONCLUSION

In this chapter, the MAS based T&D framework has been developed by utilizing a software-in-loop scheme for which $MATLAB$ and $OPENDSS$ have been employed. The developed method has been used for assessing the impact of the active distribution system and volt-var optimization (through CVR) on the ATC of the system. The ADS has been considered to be comprising of DERs, MG, and EV. Two indices $ATCE_{factor}$ and $ATCVR_{factor}$ have been proposed for assessing the ADS and CVR impact on ATC. The modified IEEE 24 BUS RTS system at transmission and cluster modified IEEE 123 BUS distribution system at distribution level have been taken as test systems for implementation of the proposed method. From the observations and results, it could be concluded that considering the ADS and CVR significantly affects the ATC of the system. This effect is minimal when the $\%ADS_{load}$ is small and enlarges with the increase in $\%ADS_{load}$. The method proposed in this work could provide critical information pertaining to ATC for real/near-real-time operation, scheduling, and planning of the power system. Further, adequate information pertaining to real-time ATC would also be viable for enhancing the resiliency of the system.