Distributed continuation power flow method for integrated transmission and active distribution network

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Abstract As the integration of distributed generations (DGs) transforms the traditional distribution network into the active distribution network, voltage stability assessments (VSA) of transmission grid and distribution grid are not suitable to be studied separately. This paper presents a distributed continuation power flow method for VSA of global transmission and distribution grid. Two different parameterization schemes are adopted to guarantee the coherence of load growth in transmission and distribution grids. In the correction step, the boundary bus voltage, load parameter and equivalent power are communicated between the transmission and distribution control centers to realize the distributed computation of load margin. The optimal multiplier technique is used to improve the convergence of the proposed method. The three-phase unbalanced characteristic of distribution networks and the reactive capability limits of DGs are considered.

Simulation results on two integrated transmission and distribution test systems show that the proposed method is effective.

Keywords Integrated transmission and distribution grid, Distributed computation, Voltage stability, Continuation power flow, Three-phase distribution network, Distribution generation

1 Introduction

The voltage collapse is one of the most serious risks for modern power systems [1]. Compare with other kinds of stability problems, the long term voltage stability problems can be simulated and approximated by using the static model and methods. In traditional voltage stability assessments (VSA), the transmission power systems (TPSs) and the distribution networks (DNs) are studied separately, which may result in inaccurate assessment results. With high penetration of distributed generations (DGs) and electric vehicles into the distribution grid, the power flows and voltage-reactive power characteristics of the distribution grids have been changed significantly [2]. As a consequence, the DNs have become increasingly active and they are not suitable to be treated as the equivalent loads in power flow analysis of TPSs [3, 4]. Thus, voltage stability problems for TPSs and DNs are not suitable to be solved separately and it is necessary to study the VSA methods for global power grid.

There are several technological challenges in solving the global power flow problem. Firstly, the transmission and distribution grids are operated and managed by different control centers in existing dispatch and control system of power grid. The models of TPSs and DNs are maintained separately and transferring models is against privacy

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protection rules, so it is hard to directly solve a whole power flow model in the field. Secondly, the transmission and distribution grids are different in voltage level, topology structure and impedance parameters, which would lead to numerical difficulties. Thirdly, the size of the integrated power system is considerably large. In addition, the three-phase unbalanced characteristic of the distribution grids is prominent while the transmission grids are balanced. A “master-slave-splitting” (MSS) based method was proposed in [5, 6]. By decomposing the global power flow into a single transmission power flow master sub-problem and multiple distribution power flow sub-problems, this method addresses the above challenges effectively.

The continuation power flow (CPF) is an important tool for assessing power system voltage stability [7–9]. The CPF method has been validated to be a good method to compute the load margins of both TPSs and DNs and it could consider the inequality constraints which describe the nonlinear characteristics of electrical components [10–17]. In [18] a distributed CPF method was presented to compute the available transfer capability (ATC) of interconnected power grid which is composed of many transmission sub-grids. Based on a reduced network equivalent model, a distributed CPF method for VSA of a transmission sub-grid within the large interconnected power grid was proposed in [19]. However, both of them cannot be directly used to solve the integrated transmission and distribution grid. In [20], an expanded CPF based on master-slave distributed method was presented to compute the total transfer capability of integrated power system. Unfortunately, because the same parameterization technique is used in CPF computation of both transmission and distribution grids in this CPF method, the uniformity of load increases of TPS and DNs and accuracy of voltage stability critical point are difficult to be guaranteed.

This paper presents a distributed continuation power flow (DCPF) method for integrated transmission and distribution grid. The transmission CPF/PF and distribution PF/CPF are run iteratively and only the load parameter, the powers and voltage phasors of the boundary buses are communicated between the control centers. The different parameterization schemes are used to realize the uniform load increase of TPS and DNs. The parameterization switching logic and the optimal multiplier Newton power flow technique are adopted to improve the convergence. The reactive capability limits of DGs in unbalanced three-phase distribution networks are also considered by using the bus type double switching logics. At last, some numerical examples are given to show the effectiveness of our method.

2 Global VSA problem formulation

Figure 1 shows the global power grid which consisting of one transmission grid and n distribution grids. In Fig. 1, the transmission and distribution grids are denoted by T and D and they are connected at the point of common couple (PCC) buses.

The global VSA problem can be formulated as follows.

$$\max \lambda \quad (1)$$

$$\text{s.t. } f_{T,p}(\mathbf{x}_{pcc}, \mathbf{x}_T) + \lambda \Delta \mathbf{P}_{T,g} = 0 \quad (2)$$

$$f_{T,q}(\mathbf{x}_{pcc}, \mathbf{x}_T) = 0 \quad (3)$$

$$f_{D_i,pcc,p}(\mathbf{x}_T, \mathbf{x}_{D_i,pcc}, \mathbf{x}_{D_i}) = 0 \quad i = 1, 2, \dots, n \quad (4)$$

$$f_{D_i,pcc,q}(\mathbf{x}_T, \mathbf{x}_{D_i,pcc}, \mathbf{x}_{D_i}) = 0 \quad i = 1, 2, \dots, n \quad (5)$$

$$f_{D_i,p}(\mathbf{x}_{D_i,pcc}, \mathbf{x}_{D_i}) - \lambda \Delta \mathbf{P}_{D_i} = 0 \quad i = 1, 2, \dots, n \quad (6)$$

$$f_{D_i,q}(\mathbf{x}_{D_i,pcc}, \mathbf{x}_{D_i}) - \lambda \Delta \mathbf{Q}_{D_i} = 0 \quad i = 1, 2, \dots, n \quad (7)$$

$$\underline{\mathbf{Q}}_{T,g} \leq \mathbf{Q}_{T,g}(\mathbf{x}_T, \mathbf{x}_{pcc}) \leq \bar{\mathbf{Q}}_{T,g} \quad (8)$$

$$\mathbf{Q}_{D_i,DG}(\mathbf{x}_{D_i}) < 0 \quad i = 1, 2, \dots, n \quad (9)$$

$$\sum_{k=1}^{n_{T,g}} \Delta P_{T,g,k} = \sum_{i=1}^n \sum_{j=1}^{n_{D_i,L}} \Delta P_{D_i,j} \quad (10)$$

where λ is the load parameter; n is the number of distribution grids; $\mathbf{x}_T$ and $\mathbf{x}_{D_i}$ are the state variable vector of the transmission grid and the state variable vector of the i^{th} distribution grid, including the bus voltage magnitudes and angles. It is necessary to note that the state variables of the PCC buses are included in $\mathbf{x}_T$ and $\mathbf{x}_{D_i}$. $\mathbf{x}_{pcc}$ and $\mathbf{x}_{D_i,pcc}$ are the n -dimensional state variable vector of the PCC buses and the i^{th} component of $\mathbf{x}_{pcc}$ respectively. $\Delta \mathbf{P}_{T,g}$, $\Delta \mathbf{P}_{D_i}$ and $\Delta \mathbf{Q}_{D_i}$ are the predefined active generation variation vector of the transmission grid, the active and reactive load variation vector of the i^{th} distribution grid. $\Delta P_{T,g,k}$ is the predefined active generation variation of the k^{th} generator of TPS. $\Delta P_{D_i,j}$ is the predefined active load variation of bus j of the i^{th} DN. $n_{T,g}$ is the number of generators, $n_{D_i,L}$ is the number of load buses of the i^{th} DN. $\mathbf{Q}_{T,g}$ is the reactive

Fig. 1 Diagram of the global power grid

output of generators. $\underline{Q}_{T,g}$ and $\bar{Q}_{T,g}$ are the lower and upper limits of $Q_{T,g}$. (2)–(3) denote the parameterized power flow equations of the transmission grid except the PCC buses. (4)–(5) are the power flow equations of the PCC buses. (6)–(7) denote the parameterized power flow equations of the distribution grids except the PCC buses. (8) are the reactive output power inequality constraints of generators. (9) are the inequality constraints of different types of DGs. (10) indicates that the sum of the real power generation variation should be equal to the sum of real power load variation.

Even though problem (1)–(10) is a kind of optimal power flow problem and it can be solved by using any OPF solvers, the CPF technique is used for solving it in this paper. The inequality constraints (8), (9) are handled by using the bus type switching scheme within the iterative solution process of the corrector. The maximum Lambda and the voltage stability critical point are obtained by reducing the step length step by step in CPF computation after the nose point has been passed. Thus the problem consisting of (2)–(7) could be solved by the global CPF method.

3 Decomposition of the global VSA problem

Traditionally, the transmission grid VSA and the distribution grid VSA are implemented by the upper level transmission control center and the lower level distribution control centers respectively and separately. In order to maintain the existing operation and computation mode of transmission and distribution grid control centers to the largest extent, the global VSA problem is decomposed into the transmission VSA sub-problem, the distribution VSA sub-problem and the communication at the PCC bus.

3.1 Transmission VSA model

The schematic diagram of independent transmission computation is shown as Fig. 2.

The mathematical model of independent transmission computation can be written as

Fig. 2 Illustration of the independent transmission computation model

$$f_{T,p}(x_{pcc}, x_T) + \lambda \Delta P_{T,g} = 0 \quad (11)$$

$$f_{T,q}(x_{pcc}, x_T) = 0 \quad (12)$$

$$f_{D_i,pcc,p}(x_T, x_{D_i,pcc}) - P_{D_i,pcc} = 0 \quad i = 1, 2, \dots, n \quad (13)$$

$$f_{D_i,pcc,q}(x_T, x_{D_i,pcc}) - Q_{D_i,pcc} = 0 \quad i = 1, 2, \dots, n \quad (14)$$

where $P_{D_i,pcc}$ and $Q_{D_i,pcc}$ are the equivalent load power, which can be computed from the power flow solutions of the i^{th} distribution grid.

The transmission grid carries out CPF computation by employing the local parameterization scheme, and its extended power flow equations can be formulated as

$$f_T(x_{pcc}, x_T) + \lambda \Delta S_{T,g} = 0 \quad (15)$$

$$x_{T,m}^{k+1} - x_{T,m}^k = \Delta x \quad (16)$$

where $\Delta S_{T,g}$ is the generation variation vector. The state variable $x_{T,m}$ denotes the voltage magnitude of bus m . The determination of m was given in [7]. The superscript k denotes the iteration number. Δx is the step length.

3.2 Distribution VSA model

The schematic diagram of i^{th} independent distribution grid computation is shown as Fig. 3.

The i^{th} distribution grid control center carries out regular power flow to guarantee the same load increase with the transmission grid control center. Its power flow equation can be formulated as

$$f_{D_i,p}(x_{D_i,pcc}, x_{D_i}) - \lambda \Delta P_{D_i} = 0 \quad (17)$$

$$f_{D_i,q}(x_{D_i,pcc}, x_{D_i}) - \lambda \Delta Q_{D_i} = 0 \quad (18)$$

where $x_{D_i,pcc}$ and λ are obtained from the transmission CPF solutions. The PCC bus is regarded as the slack bus (root bus) of the distribution grid and its load equation is not included in (17) and (18).

3.3 Communication mechanism

In each correction step of transmission CPF computation, the state variable vector x_{pcc} and load parameter λ can be obtained by solving (15, 16) and will be transmitted to each distribution grid control center. Taking $x_{D_i,pcc}$ as the

Fig. 3 Illustration of the i^{th} independent distribution grid computation model

root bus state variable of the i^{th} distribution grid, the state variable vector $\mathbf{x}_{D_i}$ can be obtained by solving (17, 18). Thus $P_{D_i,pcc}$ and $Q_{D_i,pcc}$ could be computed by using $\mathbf{x}_{D_i}$ and will be returned to the transmission grid control center. After receiving the equivalent load power of all PCC buses, the transmission grid control center repeats the corrector computation until the following convergence criteria are satisfied.

$$\max_{i=1,\dots,n} \left\{ \left| P_{D_i,pcc}^{(k+1)} - P_{D_i,pcc}^{(k)} \right| \right\} < \varepsilon \quad (19)$$

$$\max_{i=1,\dots,n} \left\{ \left| Q_{D_i,pcc}^{(k+1)} - Q_{D_i,pcc}^{(k)} \right| \right\} < \varepsilon \quad (20)$$

$$\max_{i=1,\dots,n} \left\{ \left| V_{D_i,pcc}^{(k+1)} - V_{D_i,pcc}^{(k)} \right| \right\} < \varepsilon \quad (21)$$

$$\left| \lambda^{(k+1)} - \lambda^{(k)} \right| < \varepsilon \quad (22)$$

where ε is the given tolerance. $V_{D_i,pcc}$ is the voltage magnitude of PCC bus. The distributed computation of load margin could be realized with the communication between the transmission and distribution control centers in the corrector.

4 Distributed computation of global CPF

4.1 Procedure of the proposed method

The computation procedure of the DCPF for integrated transmission and distribution grid is given as follows.

Step 1: Solve the global power flow in base case by using the distributed method to obtain the initial point of P-V curve.

Step 2: Obtain the predicted solution of transmission grid by using the tangent method.

Step 3: Implement distributed power flow in the corrector.

Step 4: Check whether the critical point has been passed. If this is true, find the critical point by reducing the step length and identify its type. Otherwise, go to step 2.

The flow chart of the proposed DCPF method is given in Fig. 4.

4.2 Parameterization switching strategy

For a predefined load increase pattern, the power flow of a distribution grid may diverge before the voltage stability critical point of transmission grid is reached in CPF computation. That is to say, the distribution grid reaches its critical point earlier. In order to handle this situation, the parameterization schemes of transmission and distribution

Fig. 4 Flow chart of the proposed distributed CPF algorithm

grids should be switched. The transmission grid carries out regular power flow as follows.

$$\mathbf{f}_T(\mathbf{x}_{D_i,pcc}, \mathbf{x}_T) + \lambda^{k+1} \Delta \mathbf{S}_{T,g} = 0 \quad (23)$$

$$\lambda^{k+1} - \lambda^k = \Delta \lambda \quad (24)$$

The distribution grid carries out CPF computation by employing the local geometric parameterization to handle the special properties of three-phase P-V curves [17]. The extended power flow equations are formulated as

$$\mathbf{f}_{D_i}(\mathbf{x}_{D_i,pcc}, \mathbf{x}_{D_i}) - \lambda \Delta \mathbf{S}_{D_i} = 0 \quad (25)$$

$$(x_{D_i,m} - x_{D_i,m}^0) - \beta(\lambda - \lambda^0) = 0 \quad (26)$$

where (26) is the local geometric parameterization equation. $x_{D_i,m}$ denotes the voltage magnitude of bus m of the i^{th} distribution grid. $(\lambda^0, x_{D_i,m}^0)$ is the reference point on λ - V plane. β is the geometric parameter.

For the cases that the parameterization switching strategy fails to solve the problem, the optimal multiplier technique [21] could be used to identify the voltage stability critical point according to the value of optimal multiplier. If the power flow becomes ill-conditioned, the

value of optimal multiplier is close to zero. In such a case, reduce the step length by half and go back to predictor until the step length is smaller than the tolerance.

4.3 Unbalanced characteristic of distribution grids

No matter the i^{th} distribution grid is unbalanced, the state variable of the root bus is always considered to be symmetric.

$$\begin{cases} V_{D_i,pcc}^a = V_{D_i,pcc}^b = V_{D_i,pcc}^c \\ \theta_{D_i,pcc}^a = \theta_{D_i,pcc}^b + 120^\circ = \theta_{D_i,pcc}^c - 120^\circ \end{cases} \quad (27)$$

where $V_{D_i,pcc}^{abc}$ and $\theta_{D_i,pcc}^{abc}$ are the three-phase voltage magnitude and angle of the root bus. $V_{D_i,pcc}^a$ and $\theta_{D_i,pcc}^a$ are obtained from the transmission CPF solutions.

$$\begin{cases} V_{D_i,pcc}^a = V_{D_i,pcc} \\ \theta_{D_i,pcc}^a = \theta_{D_i,pcc} \end{cases} \quad (28)$$

In the independent transmission computation, the equivalent load power is the summation of the three-phase power injection of the PCC bus.

$$\begin{cases} P_{D_i,pcc} = \sum_{ph=a,b,c} P_{D_i,pcc}^{ph} \\ Q_{D_i,pcc} = \sum_{ph=a,b,c} Q_{D_i,pcc}^{ph} \end{cases} \quad (29)$$

4.4 DG reactive capability limits

There are three common DG interfaces with various control characteristics and operation modes, namely synchronous generation (SG), induction generation (IG) and voltage source converter (VSC) [22, 23].

Internal combustion (IC) engine and split shaft micro-turbine (MT) are SG-interfaced DGs. The SG excitation regulations include the constant power factor regulation and the automatic voltage regulation (AVR), which are modeled as PQ bus and PV bus respectively. The PV-PQ bus type switching strategy [24] should be implemented if the reactive power injection of PV bus violates the limits.

The conventional types of wind turbine generation (WTG) are IG-interfaced, e.g., the constant speed type and the slip control type. The power factor of IG could be maintained constant by the automatic switching of shunt capacitors. If the number of switching capacitors reaches the maximum value, the IG-interfaced DGs could be modeled as PQ(V) bus of which the reactive power is function of bus voltage and active power.

Large numbers of DGs are VSC-interfaced, e.g., fuel cell (FC), photovoltaic (PV) unit, energy storage system (ESS) and doubly fed induction generation (DFIG). The VSC control strategies include voltage control and current control which can be modeled as PV and PI bus

respectively. If the injection currents of PV-type VSCs violate their limits, the corresponding bus types should be switched to the PI-type [20]. If the computed injection current of this PI bus is under limit and its bus voltage is higher than the set value, the bus type should be switched back to PV-type.

Figure 5 shows a schematic diagram of DG interfaces and control strategies.

5 Numerical simulations

Two integrated test power systems are constructed here. The test system A-33 is the combination of the IEEE-30 transmission system and IEEE-33 unbalanced distribution system. The test system B-33 is constructed by using the IEEE-118 transmission system and IEEE-33 unbalanced distribution system.

5.1 Comparisons between global VSA and separate VSAs of transmission and distribution grids

The A-33 system is used here and the IEEE-33 unbalanced distribution system is connected to the load bus 26 (PCC) of IEEE-30 transmission grid. The loads of distribution grid are increased while maintaining constant power factor and the increased active power is matched by generators of transmission grid. The following three cases are studied here.

Case 1: Carry out DCPF for the integrated system.

Case 2: Carry out independent transmission CPF while the distribution system is modeled as the equivalent load power of PCC bus.

Case 3: Carry out independent distribution CPF while the root bus voltage is assumed constant.

Fig. 5 Schematic diagram of DG interfaces and control strategies

Fig. 6 P-V curves of PCC bus in three cases

Table 1 Comparisons of load margins of three cases

Case	VSA mode	Load margin (MW)
1	DCPF	10.77
2	Transmission CPF	26.54
3	Distribution CPF	16.25

The comparison of P-V curves of PCC bus in three cases is shown in Fig. 6.

The comparison of load margin results of three cases is given in Table 1.

As is shown in Table 1, the load margin computed by the transmission CPF is much larger than that computed by DCPF. And the differences between the P-V curves of PCC bus in Case 1 and Case 2 are very large as shown in Fig. 6. This is because the essential reason leads to the voltage collapse of an integrated power system is the load increase of the distribution grid and the Jacobin matrix of integrated system becomes singular due to the singularity of the sub-matrix of the distribution grid, which cannot be reflected in the traditional independent transmission CPF. Since the three phases of distribution system are unbalanced, the weakest phase is the main reason for the voltage collapse in unbalanced DNs and has an impact on the voltage stability of the integrated system [17]. Thus the traditional independent transmission CPF may bring inaccurate computational results.

As is shown in Fig. 6, the PCC bus voltage continues to decline as the load increases in Case 1, which indicates the irrationality of the assumption that the root bus voltage is constant in traditional independent distribution CPF. Compared with the load margin in Case 3, the maximum loading of distribution grid in Case 1 is smaller because of the declination of PCC bus voltage, as shown in Table 1.

5.2 Applications of the parameterization switching strategy and the optimal multiplier technique

In order to fully test the proposed DCPF method, three computational modes on the A-33 system are considered here. The loads of the integrated grid are increased while maintaining constant power factor and the increased active power is matched by generators of transmission grid. The predefined load variations of transmission and distribution grids in the three modes are listed in Table 2.

The parameterization switching strategy and the optimal multiplier technique are adopted to handle the cases that distribution grid reaches the critical point earlier than the transmission grid in DCPF computation. The computational process and results in the three modes are shown in Table 3. The global CPF which denoted as ‘GCPF’ is run to give the benchmark results in Table 3.

In Mode 1, an accurate load margin is obtained without parameterization switching due to the smallest distribution load variations.

For Mode 2, the regular power flow of distribution grid is diverged in the 50th correction step. However, the regular power flow of transmission grid still fails to converge after switching parameterization methods. Then the optimal multiplier power flow is adopted for the distribution grid. The changing trend of the minimum eigenvalue of the distribution power flow Jacobin matrix in DCPF computation is shown in Fig. 7. Under this kind of cases, an approximate load margin could be computed before the critical point is met in DCPF computation. As is shown in Fig. 7, the minimum eigenvalue approaches to zero which indicates that the last operation point is close to critical point. The error between the computed load margin and the exact value is acceptable according to Table 3.

In Mode 3, the regular power flow of distribution grid cannot converge in the 27th correction step. An accurate load margin could be obtained by switching the parameterization methods.

5.3 Impacts of DG interconnection on voltage stability of the integrated transmission and distribution grid

Four different types of DGs are connected to the distribution system as shown in Fig. 8.

Table 2 Predefined load variations in three modes

Mode	Transmission load variations (MVA)	Distribution load variations (MVA)
1	136 + j62.2	1.863 + j1.16
2	136 + j62.2	2 × (1.863 + j1.16)
3	136 + j62.2	4 × (1.863 + j1.16)

Table 3 Computational process and results in the three modes

Mode	Parameterization	Load margin (MW)		
		DCPF		GCPF
		Correction Step	Result	
1	T: local parameterization	—	172.43	172.45
	D: regular power flow	—	—	
2	T: local parameterization	50	—	170.23
	D: regular power flow	—	—	
	Parameterization switching	50	—	
	D: optimal multiplier	—	166.44	
3	T: local parameterization	27	—	136.32
	D: regular power flow	—	—	
	Parameterization switching	—	136.37	

Parameters and bus types of each DG is given in Table 4.

In Table 4, P denotes the active output power of each DG. V is the specific voltage magnitude of PV bus. $Q_{\max}$ and $Q_{\min}$ are the upper and lower limits of reactive output power respectively. I is the specific injection current magnitude of PI bus and $I_{\max}$ is the limit of I . Q_c is the rated capacity of each capacitor and $N_{c\max}$ denotes the maximum number of switching capacitors. IC and MT are controllable DGs and their initial active output powers are 50 % of the limits.

Firstly, the DCPF is carried out on the A-33 system before and after interconnecting DGs. The predefined load variations of transmission and distribution grids are

Fig. 7 Changing trend of minimum eigenvalue of distribution power flow Jacobin matrix **Fig. 8** Types and locations of DGs in IEEE 33 bus DN**Table 4** Parameters and bus types of each DG

DG type	Bus type	Parameters
IC	PV	$P = 500 \text{ kW}$, $V = 1 \text{ p.u.}$, $Q_{\max} = 300 \text{ kvar}$, $Q_{\min} = -300 \text{ kvar}$
WTG (IG)	PQ(V)	$P = 200 \text{ kW}$, $Q_c = 50 \text{ kvar}$, $N_{c\max} = 30$
MT	PV	$P = 300 \text{ kW}$, $V = 0.98 \text{ p.u.}$, $I_{\max} = 1.2 \text{ p.u.}$
PV	PI	$P = 300 \text{ kW}$, $I = 0.08 \text{ p.u.}$

$136 + j62.2 \text{ MVA}$ and $11.18 + j6.69 \text{ MVA}$ respectively. The increased active power of distribution grid is matched by controllable DGs. The comparison of load margins is shown in Table 5.

The capability constraints of DGs are handled by using the bus type switching scheme given in Section 4.4. As is shown in Table 5, the parameterization switching strategy is used to handle the voltage collapse of distribution grid in both cases. The load margin of integrated grid is enhanced by connecting DGs to the DN.

The comparison of P-V curves of PCC bus with and without DGs is shown in Fig. 9.

Table 5 Comparisons of load margin with and without DGs

Case	Parameterization	Load margin (MW)		
		DCPF		GCPF
		Correction Step	Result	
Without DGs	T: local parameterization	20	—	108.45
	D: regular power flow	—	—	
	Parameterization switching	—	108.41	
With DGs	T: local parameterization	22	—	160.35
	D: regular power flow	—	—	
	Parameterization switching	—	159.44

Fig. 9 P-V curves of PCC bus with and without DGs

Table 6 Equivalent reactive power and voltage of PCC bus at critical point with and without DGs

Case	Equivalent reactive power of PCC (Mvar)	Voltage of PCC
Without DGs	9.5034	0.78
With DGs	-6.4844	0.88

Fig. 10 Equivalent active power of PCC bus with and without DGs

The equivalent reactive power and voltage of PCC bus at critical point before and after interconnecting DGs are given in Table 6.

As is shown in Table 6, the equivalent reactive power of PCC bus at critical point is negative after integrating DGs, which indicates that the reactive power transfers from distribution grid to transmission grid. Thus the voltage of PCC bus is supported and higher than that without DGs.

The real powers of the controllable DGs reach their limits at $\lambda = 0.15$ simultaneously. Then the increased real

Fig. 11 Voltage of the PCC bus and load parameter in DCPF computation

Fig. 12 Equivalent load power in DCPF computation

power of DN is balanced by the generators of TPS. The equivalent real powers of PCC bus with and without DGs are shown in Fig. 10.

From Fig. 10, it can be found that, at the initial stage of load increasing after connecting DGs, the equivalent real power of PCC bus is negative because the controllable DGs balance the increased real power of DN. As the output limits of the controllable DGs are reached, the equivalent real power of PCC bus becomes positive. In the DCPF process with DGs, the equivalent real power of PCC bus is much smaller than that without DGs.

Then the DCPF is applied to the B-33 system in which the distribution system is connected to the load bus 102 (PCC) of transmission grid. The communications between the transmission and distribution grids in DCPF computation are shown in Fig. 11 and Fig. 12.

On a laptop with Windows 7 64-bit, Intel Core 2.4-GHz i5 CPU, it takes about 27.343 s to trace the P-V curves

through 72 correction steps. As is shown in Fig. 12, the equivalent reactive power in DCPF computation is negative, which indicates that the distribution grid serves as a reactive source for the transmission grid due to the integration of DGs.

6 Conclusion

As the integration of DGs, the transmission and distribution grids should be studied as a whole global system. In this paper, a distributed continuation power flow method is presented for solving the VSA problem of integrated grid and the computation architecture of DCPF is developed. The transmission CPF and distribution CPFs are run iteratively and only the load parameter, the powers and voltage phasors of the boundary buses are communicated between the control centers. The parameterization switching strategy and optimal multiplier technique are employed to guarantee the convergence of the proposed method. The reactive capability limits of different type of DGs and unbalanced three-phase distribution grids are considered. Numerical simulations on two integrated test systems show that the separate VSAs of transmission and distribution grids are inaccurate. By testing different computation modes, simulation results show the effectiveness of the proposed method.

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