Three-Phase Converter Models for Unbalanced Radial Power-Flow Studies

Razvan Stoicescu, Karen Miu, *Member, IEEE*, Chika O. Nwankpa, *Member, IEEE*, Dagmar Niebur, *Member, IEEE*, and Xiaoguang Yang, *Student Member, IEEE*

***Abstract*—This paper presents a power-converter model intended for balanced and unbalanced radial power-flow studies. A three-phase steady-state model of a power converter (*ac/dc–dc/ac*) composed of a diode rectifier, a lossless *dc* link, and a pulse-width-modulated inverter is presented. Both the three-phase rectifier and the three-phase inverter are modeled as three, equivalent, Y-connected single-phase rectifiers and single-phase inverters, respectively. The model is implemented within a three-phase power-flow solver with phase representation. Simulation results on a balanced and an unbalanced 15-bus system are presented.**

***Index Terms*—ac/dc unbalanced power flow, power converter, small integrated power-distribution systems.**

I. Introduction

RECENT developments in power electronics offer the possibility of wide-scale integration within the supply network [1]. Resulting benefits would include improved control of the power delivered and improved power quality for the loads. Improved control of the power delivered would significantly impact energy management of power systems especially during critical times. Energy savings are also expected; these become an important issue with the restructuring of the power industry and the prices of natural gas, oil, and other petrochemical products.

Historically in the power industry, the main power electronics applications have been in the transmission sector where HVDC lines, solid state var compensators, unified power-flow controllers, and others have been or are in use to link *ac* systems. As a result, a number of power-flow solvers were created to handle these devices, see for example [2] and [3]. Most power-flow formulations and algorithms required the system to be three phase and balanced. This condition stemmed from the fact that protection devices on three-phase converters activate as soon as unbalanced conditions are sensed. Thus a per-phase equivalent circuit is used in [4] and [5], while in [6] balanced three-phase conditions are assumed.

Gradually, the use of power electronics is moving into power distribution systems. Power distribution systems are unbalanced systems consisting of single, two, and three-phase components and subsystems. For this reason, the previous approaches are not suitable for power distribution systems. Therefore, this paper presents a new, three-phase converter system model (rectifier, *dc* link, inverter) that can be used for balanced and unbalanced radial power systems, such as certain terrestrial distribution systems, shipboard power systems, and alternative energy source-based systems.

This paper presents a modeling approach using three, single-phase, grounded, Y-connected converters which are equivalent to actual three-phase converters. This model can also be used for other power-electronic-based equipment such as unified power controllers (UPCs), dynamic voltage regulators (DVARs), and dynamic-static compensators (D-STATCOM). The Y-connected model is designed to be equivalent to a three-phase converter with respect to the average *dc* current through the *dc* link. Since distribution systems are normally operated in a radial manner, the model presented in this paper assumes power flows from the rectifier into the *dc* link and then to the inverter. The model uses individual phase converters to capture the imbalance in the *ac* supply system. It can be used for single- and three-phase studies.

The rectifiers are assumed to be uncontrolled, diode bridge rectifiers and the inverters are voltage-controlled inverters. For bidirectional flow analysis, a controllable rectifier is needed to replace a diode rectifier. The model is then integrated into an unbalanced power-flow solver. Phase coordinates are selected for the converter models and the subsequent unbalanced distribution power-flow analysis. We make this selection because typical distribution systems experience a significant level of imbalance and, when such a case occurs, the computational advantage that comes from using symmetrical components diminishes [7]. Two prominent methods for *ac/dc* power flow have been developed: sequential methods that iterate alternatively between updates of the two sides of the converter [8], [9] and unified methods that combine power and harmonic flow, [10], [11]. The converter model proposed in this paper is implemented in a sequential power-flow solver; see also [12].

II. Converter Models

This section presents a model for three-phase power converters in radial networks shown in Fig. 1. The rectifiers are assumed to be uncontrolled, diode bridge rectifiers and the inverters are voltage-controlled inverters. The portion of the network between the main power source and the rectifier will be referred to as the *ac side of the rectifier*, while the portion of the network where average power is leaving the inverter will be referred to as the *ac side of the inverter*.

Manuscript received October 12, 2001; revised April 1, 2002. This work was supported by the Office of Naval Research Under Grants N00014-98-1-0573 and ONR N0014-01-1-0760.

R. Stoicescu is with EMA, Inc., Philadelphia, PA 19053 USA.

K. Miu, C. O. Nwankpa, D. Niebur, and X. Yang are with the Center for Electric Power Engineering, Drexel University, Philadelphia, PA 19104 USA (e-mail: Miu@ece.drexel.edu; Nwankpa@ece.drexel.edu; Niebur@ece.drexel.edu; xgyang@io.ece.drexel.edu).

Digital Object Identifier 10.1109/TPWRS.2002.804942

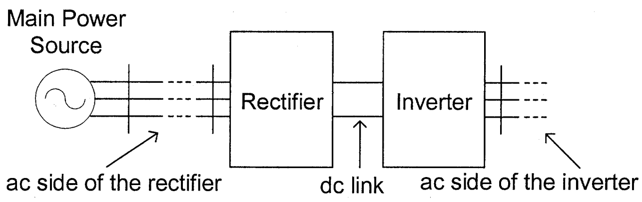

Fig. 1. Power converter setup.

The three-phase power converter is modeled by combining a A) rectifier model, B) *dc*-link, and C) inverter model. The details of each model are now presented.

A. *Rectifier Model*

The equivalent model for a three-phase rectifier is now derived. Specifically, we propose to model a three-phase full-bridge diode rectifier with three equivalent, grounded Y-connected, single-phase diode rectifiers; see Fig. 2.

Each of the three, single-phase rectifiers just discussed has the following characteristics.

i) Each rectifies the phase voltage for one phase.
ii) Their output voltages are in parallel with the *dc* link.
iii) Their output currents add and their sum over a period gives the current through the *dc* link.

Usually, the voltage in the *dc* link is sustained using capacitors. Also, capacitors and inductors are used as filters designed to reduce the harmonic content. Therefore, the *dc* voltage, V_d, and average *dc* current, I_d, are assumed to be constant and free of harmonics.

Thus, to model a three-phase rectifier using the topology in Fig. 2, a relationship between *ac* and *dc* currents of the actual three-phase rectifier and the model containing three individual rectifiers have to be established. More precisely, the *dc* currents, leaving each individual rectifier, must be equivalent to the *dc* current that would evolve from one three-phase rectifier. Hence, we first determine and then make an equivalent of the average *dc* currents.

1) Determining the dc Current: The *ac* currents entering the respective rectifiers are

$$i_a(t) = \sqrt{2}I_{ac}^a \sin(\omega t + \varphi_a) \quad (1)$$
$$i_b(t) = \sqrt{2}I_{ac}^b \sin(\omega t + \varphi_b) \quad (2)$$
$$i_c(t) = \sqrt{2}I_{ac}^c \sin(\omega t + \varphi_c) \quad (3)$$

where I_{ac}^a, I_{ac}^b, and I_{ac}^c are the RMS values and φ_a, φ_b, and φ_c are the phase angles of the three *ac* currents with respect to $v_a(t)$.

In order to sum the output currents, we choose phase a as a reference with reference angle φ_a; then

$$\varphi_{ab} = \varphi_a - \varphi_b \quad (4)$$
$$\varphi_{ac} = \varphi_a - \varphi_c. \quad (5)$$

To determine the average *dc* current leaving each single-phase rectifier, we integrate the input currents over one and the same period is used to determine the root-mean-square (RMS) values on the *ac* side of the rectifier, here 0 to 2π for the phase a reference. Average currents leaving phase a, b, and c rectifiers are

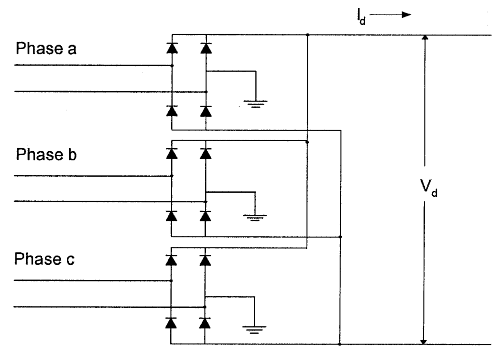

Fig. 2. Equivalent model using three Y-connected single-phase rectifiers.

$$\begin{aligned} I_d^a =& \frac{1}{2\pi}\int_0^{\pi} \sqrt{2}I_{ac}^a \sin(\omega t) d(\omega t) \\ &- \frac{1}{2\pi}\int_{\pi}^{2\pi} \sqrt{2}I_{ac}^a \sin(\omega t) d(\omega t) \\ =& 0.9I_{ac}^a \end{aligned} \quad (6)$$

$$\begin{aligned} I_d^b =& -\frac{1}{2\pi}\int_0^{\varphi_{ab}} \sqrt{2}I_{ac}^b \sin(\omega t - \varphi_{ab}) d(\omega t) \\ &+ \frac{1}{2\pi}\int_{\varphi_{ab}}^{\varphi_{ab}+\pi} \sqrt{2}I_{ac}^b \sin(\omega t - \varphi_{ab}) d(\omega t) \\ &- \frac{1}{2\pi}\int_{\varphi_{ab}+\pi}^{2\pi} \sqrt{2}I_{ac}^b \sin(\omega t - \varphi_{ab}) d(\omega t) \\ =& 0.91_{ac}^b \end{aligned} \quad (7)$$

$$\begin{aligned} I_d^c =& \frac{1}{2\pi}\int_0^{\varphi_{ac}-\pi} \sqrt{2}I_{ac}^c \sin(\omega t - \varphi_{ac}) d(\omega t) \\ &- \frac{1}{2\pi}\int_{\varphi_{ac}-\pi}^{\varphi_{ac}} \sqrt{2}I_{ac}^c \sin(\omega t - \varphi_{ac}) d(\omega t) \\ &+ \frac{1}{2\pi}\int_{\varphi_{ac}}^{2\pi} \sqrt{2}I_{ac}^c \sin(\omega t - \varphi_{ac}) d(\omega t) \\ =& 0.91_{ac}^c. \end{aligned} \quad (8)$$

The current through the *dc* link is the sum of the currents entering the rectifiers over one period. The average value of the current through the *dc* link for the Y-connected model $I_d^{3\text{-}Y}$ equals the sum of the average currents leaving each phase of the rectifier model

$$I_d^{3\text{-}Y} = I_d^a + I_d^b + I_d^c \quad (9)$$
$$= 0.9\left(I_{ac}^a + I_{ac}^b + I_{ac}^c\right). \quad (10)$$

Note that for an unbalanced three-phase network, I_{ac}^a, I_{ac}^b, and I_{ac}^c are not equal. Thus, the contributions of each rectifier are not equal. We now capture this difference by determining participation coefficients λ_a, λ_b, and λ_c for each rectifier. These participation coefficients will be used to make equivalent the sum of the average *dc* currents for the three Y-connected rectifiers with the average *dc* current of a three-phase rectifier.

2) Determining Participation Coefficients: Participation coefficients are calculated based on the network imbalance on the *ac* side of the rectifier. The participation coefficient for phase a

is taken as the ratio of I_d^a to the sum of the currents leaving each rectifier

$$\lambda_a = \frac{I_d^a}{I_d^a + I_d^b + I_d^c} \quad (11)$$
$$= \frac{I_{ac}^a}{I_{ac}^a + I_{ac}^b + I_{ac}^c}. \quad (12)$$

Similarly, λ_b and λ_c follow:

$$\lambda_b = \frac{I_{ac}^b}{I_{ac}^a + I_{ac}^b + I_{ac}^c} \quad (13)$$
$$\lambda_c = \frac{I_{ac}^c}{I_{ac}^a + I_{ac}^b + I_{ac}^c}. \quad (14)$$

Applying the participation coefficients λ_a, λ_b, and λ_c to the *dc* current for the Y-connected rectifiers $I_d^{3\text{-}Y}$ yields

$$I_d^{3\text{-}Y} = 0.9\left(1 + \frac{\lambda_b}{\lambda_a} + \frac{\lambda_c}{\lambda_a}\right) I_{ac}^a. \quad (15)$$

We now investigate the relationship between the sum of the average *dc* currents from our three, single-phase, Y-connected rectifier model and the average *dc* current from a three-phase rectifier.

3) Equivalencing the dc Current From the Model With That of a Three-Phase Rectifier: If the three-phase rectifier is a three-phase diode bridge rectifier, the average value of the current through the *dc* link can be obtained by integrating it over a period which is $\pi/3$ for a three-phase diode rectifier. $I_d^{3-\text{phase}}$ is the average value of the current through the *dc* link when the rectifier is modeled as a three-phase diode bridge rectifier. Three-phase rectifiers typically assume balanced inputs; thus with balanced conditions in the three-phase *ac* circuit, we obtain

$$I_d^{3-\text{phase}} = \frac{1}{\frac{\pi}{3}} \int_{-\pi/6}^{\pi/6} \sqrt{2} I_{ac}^a \cos(\omega t) d(\omega t) = 1.35 I_{ac}^a. \quad (16)$$

In order to make the two models equivalent, an equivalence coefficient K is defined. K is the ratio of the average value of the *dc* current when the rectifier is modeled as a three-phase rectifier *to* the *dc* current when the rectifier is modeled as three, single-phase, Y-connected rectifiers

$$K = \frac{I_d^{3-\text{phase}}}{I_d^{3\text{-}Y}}$$
$$= \frac{1.35}{0.9\left(1 + \frac{\lambda_b}{\lambda_a} + \frac{\lambda_c}{\lambda_a}\right)} \quad (17)$$
$$= \frac{1.5}{1 + \frac{\lambda_b}{\lambda_a} + \frac{\lambda_c}{\lambda_a}}. \quad (18)$$

The equivalence coefficient K relates the equivalent model using three single-phase converters to a model using a three-phase converter, through a current ratio. Note that K must be determined based on the specific type of rectifier used.

B. DC Link Model

Under the assumption that the harmonics injected by the rectifier and the inverter can be neglected, the *dc* link is modeled as a pure *dc* circuit. The real power P_d transferred through a lossless *dc* link is obtained as the product of the *dc* voltage V_d and the average value of the current through the *dc* link, $I_d^{3-\text{phase}}$:

$$P_d = V_d \times I_d^{3\text{-phase}}. \quad (19)$$

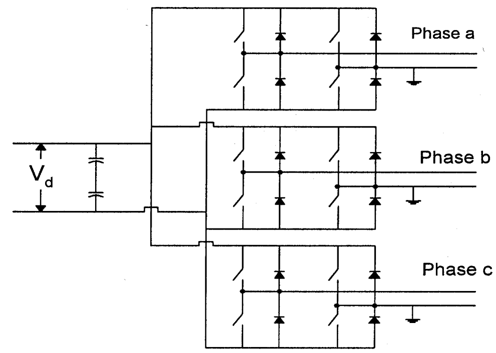

Fig. 3. Three Y-connected single-phase inverters.

C. Inverter Model

The three-phase inverter is modeled as three, equivalent, grounded Y-connected, single-phase voltage source inverters shown in Fig. 3. Each of the three inverters is a grounded, single-phase, pulse-width-modulated inverter. Their common input is the voltage in the *dc* link V_d, and their output will be a phase-to-ground voltage for phases a, b, and c. By selecting proper switching schemes, these three output voltages can be controlled and the *ac* bus to which the inverter is connected is modeled as a voltage-specified bus.

For a single-phase pulse-width-modulated inverter using unipolar switching [3], having the amplitude modulation ratio $m_a < 1$, we obtain

$$\hat{V}_1 = m_a * V_d \quad (20)$$

where $\hat{V}_1$ is the amplitude of the fundamental voltage waveform. Each equivalent single-phase inverter produces the same amplitude for its subsequent *ac* phase voltage.

D. Analog-To–Digital/Digital-To-Analog Converter

When the models for the three-phase rectifier, *dc* link and the three-phase inverter are combined, the integration limits for the average values of the currents leaving each rectifier on phases a, b, and c change. However, since we have assumed the voltage to be constant and harmonic free, we can obtain the contribution from each rectifier by using the equivalance coefficient K and the participation coefficients.

Specifically, this converter model is designed for sequential power-flow methods. As such, the real power transferred through the converter can be determined from the voltage set point of the inverter and the *ac* side of the inverter. Consequently, $I_d^{3-\text{phase}}$ can be determined. Using (17) and the equivalence coefficient, the equivalent average *dc* current out of the three, single-phase rectifiers $I_d^{3\text{-}Y}$ can be obtained. Then, using the participation coefficients λ_a, λ_b, and λ_c

$$I_d^a = \lambda_a I_d^{3\text{-}Y}$$
$$I_d^b = \lambda_b I_d^{3\text{-}Y}$$
$$I_d^c = \lambda_c I_d^{3\text{-}Y}$$

and the RMS currents flowing into the rectifier can be obtained using (6)–(8).

III. Power-Flow Solution Algorithm

A sequential power-flow solver is developed to handle radial, three-phase, unbalanced power systems with converters using the converter model presented before. The following steps outline the power-flow procedure.

Step 1) If a converter exists, divide the network into two separate *ac* subnetworks, based on the position of the converter.

Step 2) Solve the *ac* side of the inverter.

- Step 2.a) Treat the inverter bus as a voltage-specified bus and solve three-phase power flow.
- Step 2.b) Calculate the complex power leaving the inverter bus over all three phases. The total real power transferred through the converter is P_d.

Step 3) Determine the participation coefficients.

- Step 3.a) Model the converter and the *ac* side of the inverter as a lumped three-phase balanced constant power load attached to the rectifier bus using the complex power from Step 2.b. Note that reactive power is assumed equal on both sides of the converter only when determining λ_a, λ_b, and λ_c. This assumption is released when solving power-flow iterations.
- Step 3.b) Apply backward-forward sweeps to the *ac* side of the rectifier resulting in approximate branch currents.
- Step 3.c) Use the currents to determine the participation coefficients. Note that these participation coefficients do not change as long as the network topology and the load's power factors do not change.

Step 4) Solve the converter model, starting with the inverter.

- Step 4.a) Determine the voltage V_d in the *dc* link using (20).
- Step 4.b) Determine I_d using (19).
- Step 4.c) Use the equivalence coefficient K to obtain the equivalent average value of the current through the *dc* link using (18).
- Step 4.d) Use λ_a, λ_b, and λ_c to determine the average *dc* currents leaving the three, single-phase rectifiers.
- Step 4.e) Use the rectifier model to determine the magnitude of the *ac* currents entering the three rectifiers, on each phase.

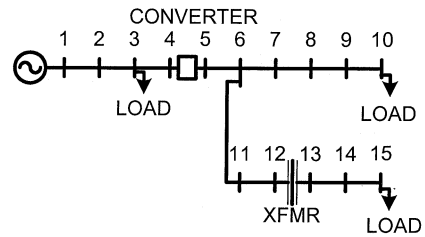

Fig. 4. One-line diagram of the 15-bus network system.

TABLE I
NOMINAL POWER LOADS FOR THE 15-BUS NETWORK IN [MW, MVAR]

Bus	*P+jQ; Phase a*	*P+jQ; Phase b*	*P+jQ; Phase c*
3	0.2000+j0	0.4000+j0	0.8000+j0
10	0.5333+j0.2666	0.5333+j0.2666	0.5333+j0.2666
15	0.5333+j0.2666	0.5333+j0.2666	0.5333+j0.2666

Step 5) Solve the *ac* side of the rectifier.

- Step 5.a) Treat the *ac* rectifier bus as a specified $P|I|$ bus. A balanced real power is determined from Step 2.b, and the individual single-phase rectifier current magnitudes from Step 4.e are treated as constant current magnitudes on the rectifier bus. Note, for the power-flow analysis, the reactive power injected at the *ac* rectifier bus is not specified.
- Step 5.b) Solve three-phase *ac* power flow for the network on the rectifier side.

IV. Simulation Results

The power-flow algorithm was tested on a radial, three-phase 15-bus test network shown in Fig. 4. Bus 1 is the main power source bus and this network contains

- a two-stage (*ac/dc–dc/ac*) power converter placed between buses 4 and 5;
- one unbalanced load at bus 3;
- two balanced loads at buses 10 and 15;
- a grounded-Y to grounded-Y transformer connected between buses 12 and 13 (XFMR).

Two different loading conditions (a) balanced loads and (b) unbalanced loads and system will now be studied.

Case A*:*

In this case, the network on the *ac* side of the inverter is balanced with balanced loads provided in Table I. Loads are modeled as constant impedance. The voltage source and the inverter bus are specified at a 1.0 p.u., balanced, flat start.

The *ac/dc* power flow is solved for the test network; simulation results are presented in the following tables.

- Table II presents the bus voltage magnitudes for each phase.
- Table III presents the power delivered to the loads calculated from the power-flow solution.
- Table IV presents the participation coefficients determined for each phase connected to the rectifier.
- Table V presents the ac currents entering the rectifier.
- Table VI presents the calculated power on both sides of the converter.

TABLE II
BUS VOLTAGE MAGNITUDES

	V_a [pu]	V_b [pu]	V_c [pu]
Bus 1	1.000000	1.000000	1.000000
Bus 2	0.999152	0.998851	0.998781
Bus 3	0.998305	0.997702	0.997562
Bus 4	0.997426	0.996822	0.996682
Bus 5	1.000000	1.000000	1.000000
Bus 6	0.999379	0.999379	0.999379
Bus 7	0.999067	0.999067	0.999067
Bus 8	0.998756	0.998756	0.998756
Bus 9	0.998445	0.998445	0.998445
Bus 10	0.998134	0.998134	0.998134
Bus 11	0.999069	0.999069	0.999069
Bus 12	0.998759	0.998759	0.998759
Bus 13	0.992835	0.992835	0.992835
Bus 14	0.992525	0.992525	0.992525
Bus 15	0.992216	0.992216	0.992216

TABLE III
POWER DELIVERED TO THE LOADS IN [MW, MVAR]

Bus	P+jQ; Phase a	P+jQ; Phase b	P+jQ; Phase c
3	0.1993	0.3982	0.7961
10	0.5313+j0.2657	0.5313+j0.2657	0.5313+j0.2657
15	0.5251+j0.2625	0.5251+j0.2625	0.5251+j0.2625

TABLE IV
PARTICIPATION COEFFICIENTS FOR PHASES a, b, AND c

λ_a	λ_b	λ_c
0.333184	0.333385	0.333431

TABLE V
AC CURRENTS ENTERING THE RECTIFIER ON PHASES a, b, AND c IN [P.U. MAGNITUDE ∠ ANGLE]

i_{ac}^a	i_{ac}^b	i_{ac}^c
0.04991 ∠ -50.33	0.04994 ∠ -170.33	0.04995 ∠ 69.63

TABLE VI
POWER ENTERING (4) AND LEAVING (5) THE CONVERTER IN [MW, MVAR]

Bus	P+jQ; Phase a	P+jQ; Phase b	P+jQ; Phase c
4	1.0587+j1.2777	1.0587+j1.2777	1.05874+j1.2779
5	1.0587+j0.5363	1.0587+j0.5363	1.05874+j0.5363

The real power transferred through the converter is 3.1762 MW, which accounts for the real power drawn by the loads at bus 10 and 15 and the real-power loss due to line resistance. The load at bus 3 is unbalanced, and this imbalance is reflected in the participation coefficients. These are then used to determine the participation of each phase to the current through the *dc* link.

In this case, the calculated bus voltages on the *ac* side of the inverter are balanced because of

1) the network itself;
2) the loads;
3) the controlled inverter bus voltages, which are all balanced.

These voltages are not affected by the imbalance on the *ac* side of the rectifier. On the other hand, if the inverter side contains unbalanced loads, the downstream bus voltages will be unbalanced and the power-flow solution will reflect this. This is now illustrated in following case.

TABLE VII
BUS VOLTAGE MAGNITUDES

	V_a [pu]	V_b [pu]	V_c [pu]
Bus 1	1	1	1
Bus 2	0.999098	0.998797	0.998727
Bus 3	0.998197	0.997594	0.997454
Bus 4	0.997264	0.996661	0.99652
Bus 5	1	1	1
Bus 6	0.999222	0.999428	0.999371
Bus 7	0.998911	0.999116	0.99906
Bus 8	0.9986	0.998805	0.998748
Bus 9	0.998289	0.998494	0.998437
Bus 10	0.997978	0.998182	0.998126
Bus 11	0.998756	0.999166	0.999053
Bus 12	0.998289	0.998905	0.998735
Bus 13	0.990144	0.99298	0.992812
Bus 14	0.989679	0.992719	0.992495
Bus 15	0.989215	0.992459	0.992177
Bus 16	0.989058		

TABLE VIII
POWER DELIVERED TO THE LOADS IN [MW, MVAR]

Bus	P+jQ; Phase a	P+jQ; Phase b	P+jQ; Phase c
3	0.1993	0.3981	0.7959
10	0.5312+j0.2656	0.5314+j0.2657	0.5313+j0.2657
15	0.5219+j0.2609	0.5253+j0.2627	0.5250+j0.2625
16	0.1956+j0.0978		

TABLE IX
PARTICIPATION COEFFICIENTS FOR PHASES a, b, AND c

λ_a	λ_b	λ_c
0.333184	0.333385	0.333431

TABLE X
AC CURRENTS ENTERING THE RECTIFIER ON PHASES a, b, AND c IN [P.U. MAGNITUDE ∠ ANGLE]

i_{ac}^a	i_{ac}^b	i_{ac}^c
0.052972 ∠ -50.33	0.053005 ∠ -170.34	0.053016 ∠ 69.62

TABLE XI
POWER ENTERING (4) AND LEAVING (5) THE CONVERTER IN [MW, MVAR]

Bus	P+jQ; Phase a	P+jQ; Phase b	P+jQ; Phase c
4	1.1234+j1.3560	1.1234+j1.3561	1.1234+j1.3562
5	1.2524+j0.6391	1.0587+j0.5364	1.0588+j0.5361

Case B*:*

A single-phase line is added on bus 15 and leads to a bus 16 with a $0.2 + j0.1$ MW single-phase constant impedance load. All remaining loads are the same as those in Table I from Case A. The simulation results are presented in Tables VII–XI.

- Table VII presents the bus voltage magnitudes for each phase.
- Table VIII presents the power delivered to the loads calculated from the power-flow solution.
- Table IX presents the participation coefficients determined for each phase connected to the rectifier.

- Table X presents the *ac* currents entering the rectifier.
- Table XI presents the power on both sides of the converter.

In Table XI, it can be seen that the three-phase power injected into the *ac* system from the inverter is unbalanced, due to the single-phase load on bus 16. Also, imbalance exists in the unbalanced voltage magnitudes from Table VII.

V. Conclusion

A three-phase power-converter model is presented in this paper. This model consists of three single-phase, Y-connected rectifiers and inverters. It can be used for single- and three-phase networks including unbalanced networks which are frequently encountered in power distribution systems.

The model is dependent on the type of rectifiers and inverters that are used. In this paper, an equivalence coefficient is derived for full-bridge diode rectifiers. This equivalence coefficient relates the three single-phase converters to an actual three-phase converter. The model was successfully implemented into a sequential, radial three-phase power flow solver and simulation results on a 15-bus test system with one converter were presented.

References

[1] N. Mohan, T. Undeland, and W. Robbins, *Power Electronics*. New York: Wiley, 1995.

[2] J. Reeve, G. Fahmy, and B. Stott, “Versatile load flow method for multiterminal HVDC systems,” *IEEE Trans. Power App. Syst.*, vol. PAS-96, pp. 925–933, May/June 1977.

[3] M. Hasson and E. Stanek, “Analysis techniques in *ac–dc* power systems,” *IEEE Trans. Ind. Applicat.*, vol. IA–17, pp. 473–480, Sept./Oct. 1981.

[4] Y. Fan, D. Niebur, and C. Nwankpa, “Multiple power flow solutions of small integrated *ac–dc* power systems,” in *Proc. ISCAS* , Geneva, Switzerland, May.

[5] Y. K. Fan, D. Niebur, C. O. Nwankpa, H. Kwatny, and R. Fischl, “Saddle-node bifurcations of voltage profiles of small integrated AC/DC power systems,” in *Proc. IEEE Summer Meeting*, Seattle, WA, July 16–21, 2000.

[6] J. Arillaga and B. Smith, *AC–DC Power Systems Analysis*. London, U.K.: Inst. Elect. Eng., 1988.

[7] W. H. Kersting and W. H. Phillips, “Distribution feeder line models,” *IEEE Trans. Ind. Applicat.*, vol. 31, pp. 715–720, Jul./Aug. 1995.

[8] C. Callaghan and J. Arrillaga, “A double iterative algorithm for the analysis of power and harmonic flows at *ac–dc* terminals,” *Proc. Inst. Elect. Eng. Gen. Transm. Dist.*, no. 136, pp. 319–324, Nov. 1989.

[9] C. Ong and H. Fudeh, “A general purpose multiterminal *dc* load flow,” *IEEE Trans. Power App. Syst.*, vol. PAS-100, pp. 3166–3174, July 1981.

[10] D. Braunagel, L. Kraft, and J. Whysong, “Inclusion of converter and transmission equations directly in a Newton power flow,” *IEEE Trans. Power Apparat. Syst.*, vol. PAS-95, pp. 76–78, Jan. 1976.

[11] D. Tylavsky and F. Trutt, “The Newton-Raphson load flow applied to *ac/dc* systems with commutation impedance,” *IEEE Trans. Ind. Applicat.*, vol. IA-19, pp. 940–948, Nov./Dec 1983.

[12] R. Stoicescu, “Three-phase converter models for power flow studies of small integrated ac/dc power systems,” Masters Thesis, Drexel Univ., Philadelphia, PA, 2000.

Razvan Stoicescu received the B.Sc. degree in electrical engineering from the Politehnica University of Bucharest, Bucharest, Romania, in 1995 and the M.Sc. degree in electrical engineering from Drexel University, Philadelphia, PA, in 2000.

Currently, he is a Systems Engineer at EMA, Inc., Philadelphia, addressing software and configurations pertaining to distributed process control systems. He has also held positions at ASA Company, Bucharest, Romania.

Mr. Stocescu received the Drexel University Dean’s Fellowship Award in 1988.

Karen Miu (M’98) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, NY.

Currently, she is an Assistant Professor in the Electrical and Computer Engineering Department, Drexel University, Philadelphia, PA. Her research interests include distribution system analysis, distribution automation, and optimization techniques applied to power systems.

Dr. Miu received the 2000 NSF Career award and the 2001 ONR Young Investigator Award.

Chika O. Nwankpa (S’88–M’90) received the Magistr Diploma degree in electric power systems from Leningrad Polytechnical Institute, Leningrad, USSR, in 1986, and the Ph.D. degree in electrical and computer engineering from the Illinois Institute of Technology, Chicago, in 1990.

Currently, he is a Professor of Electrical and Computer Engineering at Drexel University, Philadelphia, PA. His research interests are in the areas of power systems and power electronics.

Dr. Nwankpa is a recipient of the 1994 Presidential Faculty Fellow.

Dagmar Niebur (M’88) received the Diploma degree in mathematics and physics from the University of Dortmund, Dortmund, Germany, in 1984, the degree in computer science in 1987, and the Ph.D. degree in electrical engineering in 1994 from the Swiss Federal Institute of Technology, Lausanne, Switzerland.

Currently, she is an Assistant Professor in the Electrical and Computer Engineering Department at Drexel University, Philadelphia, PA. She has also held research positions at the Jet Propulsion Laboratory, Pasadena, CA, and the Swiss Federal Institute of Technology, Pasadena, CA. She was also in a computer engineering position at the University of Lausanne. Her research focuses on intelligent information processing techniques for power system monitoring and control.

Dr. Niebur is a recipient of the 2000 NSF CAREER award.

Xiaoguang Yang (S’99) received the B.Sc. and M.Sc. degrees from Xi’an Jiaotong University, Xi’an, China, in 1994 and 1997, respectively. He received the second M.Sc. degree from the Electrical and Electronic Engineering Department, Nanyang Technological University, Singapore, in 1999. He is currently pursuing the Ph.D. degree in the Electrical and Computer Engineering Department, Drexel University, Philadelphia, PA.