6 REFERENCES

[1]. U. Jayatunga, S. Perera, And P. Ciufo, “Impact Of Mains Connected Three-Phase Induction Motor Loading Levels On Network Voltage Unbalance Attenuation,” In Power System Technology (Powercon), 2012 Ieee International Conference On, 2012, Pp. 1–6.

[2]. IEC/TR 61000-3-13: Electromagnetic Compatibility (Emc) - Limits - Assessment Of Emission Limits For The Connection Of Unbalanced Installations To Mv, Hv And Ehv Power Systems, Ed. 1. Technical Report, International Electro Technical Commission, 2008.

[3]. IEC/TR 61000-3-6: Electromagnetic Compatibility (Emc) - Limits – Assessment Of Emission Limits For Distorting Loads In Mv And Hv Power Systems, Ed. 1technical Report, International Electrotechnical Commission, 1996.

[4]. IEC/TR 61000-3-7: Electromagnetic Compatibility (Emc) - Limits – Assessment Of Emission Limits For Fluctuating Loads In Mv And Hv Power Systems, Ed.1. Technical Report, International Electrotechnical Commission, 1996.

[5]. P. Pillay And M. Manyage. Definitions Of Voltage Unbalance. Ieee Power Engineering Review, 21(5):49–51, May 2001

[6]. J. Driesen, T. Van Craenenbroeck, Voltage Disturbances, Copper Development Association, May 2002

[7]. IEC Ts 60034-26: Effects Of Unbalanced Voltages On The Presence Of Three-Phase Induction Motors. International Electrotechnical Commission, 2002.

[8]. Von Jouanne And B. Banerjee, "Assessment Of Voltage Unbalance," Ieee Transactions On Power Delivery, Vol. 16, Pp. 782-790, 2001.

[9]. L. Moran, P. Ziogas, G. Joos, "Design Aspects Of Synchronous Pwm Rectifier inverter Systems Under Unbalanced Input Voltage Conditions", Ieee Transactions On Industry Applications, Vol. 28, Pp. 1286-1293, 1992.

[10]. K. Lee, G. Venkataramanan, T. M. Jahns, "Modeling Effects Of Voltage Unbalances In Industrial Distribution Systems With Adjustable-

Speed Drives", Ieee Transactions On Industry Applications, Vol. 44, Pp. 1322-1332, 2008

[11]. V. O. Zambrano, E. B. Makram, R. G. Harley, “Stability Of A Synchronous Machine Due To An Unsymmetrical Fault In Unbalanced Power System”. In Proc. Of 20th Southeastern Symposium On System Theory, Pp. 231-235, 1988

[12]. R. Salustiano, E. Neto, M. Martine, “The Unbalanced Load Cost On Transformer Losses At A Distribution System”, In 22th International Conference On Electricity Distribution (Cired), Stockholm, 2013.

[13]. D. P. Manjure And E. B. Makrram, “Impact Of Unbalance On Power System Harmonics”. In Proc. 10th International Conference On Harmonics And Quality Of Power (Ichqp 2002), Vol. 1, Pp. 328-333, 2002.

[14]. J. Kuang, S. A. Boggs, “Pipe-Type Cable Losses For Balanced And Unbalanced Currents”. Ieee Transactions On Power Delivery, Vol. 17, No.2, Pp.313-317, 2002.

[15]. L. S. Czarnecki, “Power Related Phenomena In Three-Phase Unbalanced Systems”. Ieee Transactions On Power Delivery, Vol. 10, No.3, Pp.1168-1176, 1995.

[16]. C. A. Reineri, J. C. Gomez, E. Belenguer B., M. Felici, “Revision Of Concepts And Approaches For Unbalance Problems In Distribution”, In Proc. Of Transmission & Distribution Conference And Exposition, Aug 2006.

[17]. Campos, G. Joos, P. D. Ziogas, J. F. Lindsay, "Analysis And Design Of A Series Voltage Compensator For Three-Phase Unbalanced Sources", Ieee Transactions On Industrial Electronics, Vol. 39, Pp. 159-167, 1992

[18]. Farzanehrafat And N. Watson, “Review Of Power Quality State Estimation,” In Universities Power Engineering Conference (Aupec), 2010 20th Australasian, 2010, Pp. 1–5.

[19]. K. K. C. Yu And N. Watson, “Three-Phase Harmonic State Estimation Using Svd For Partially Observable Systems,” In Power System Technology, 2004. Powercon 2004. 2004 International Conference On, Vol. 1, 2004, Pp. 29–34 Vol.1.

[20]. M. Crow, Computational Methods For Electric Power Systems, L. Grigsby, Ed. Boca Raton, Florida: Crc Press Llc, 2003.Schweppe F, Wildes J, And Rom D. “Power System Static State Estimation: Parts I, Ii, And Iii”. Denver, Colorado: Power Industry Computer Conference (Pica), June, 1969.

[21]. H.M. Beides And G. T. Heydt, "Dynamic State Estimation Of Power System Harmonics Using Kalman Filter Methodology", IEEE Trans. On Power Delivery, Vol. 6, Pp. 1663-1670, 1991.

[22]. Z.P. Du, J. Arrillaga, N.R. Watson & S. Chen, "Identification Of Harmonic Sources Of Power Systems Using State Estimation", Generation, Transmission And Distribution, Iee Proceedings-, Vol. 146, Pp. 7-12, 1999.

[23]. N. Lu, J. H. Teng, And W. H. E. Liu, "Distribution System State Estimation," IEEE Transactions On Power Systems, Vol. 10, No. 1, Pp. 229-240, 1995.

[24]. K. Li, "State Estimation For Power Distribution Systems And Measurement Impacts," IEEE Transactions On Power Systems, Vol. 11, No. 2, Pp. 911-916, 1996.

[25]. W. Hansen, "Power System State Estimation Using Three-Phase Models," IEEE Transactions On Power Systems, Vol. 10, No. 2, Pp. 818-824, 1995.

[26]. U.Jayatunga, S.Perera, and P.Ciufo, Voltage unbalance emission assessment in radial power systems, Power Delivery, IEEE Transactions on, vol. 27, no.3, pp. 16531661, 2012.

[27]. U. Jayatunga, S. Perera, P. Ciufo, and A. Agalgaonkar, Voltage unbalance emission assessment in interconnected power systems, pp. 11, 2013.

7 Appendix 1

Three bus interconnection system data

Phase impedance values in ohm per kilometre & Load impedance connect at busbar 2,3 shown below

$$([Z_{abc}]/km) = \begin{bmatrix} 0.40+j0.40 & 0.05+j0.09 & 0.01+j0.05 \\ 0.05+j0.09 & 0.40+j0.40 & 0.05+j0.09j \\ 0.01+j0.05 & 0.05+j0.09 & 0.40+j0.40 \end{bmatrix}$$

	Phase a	Phase b	Phase c
$[Z_{L2}](\Omega)$	$50+j38$	$60+j19$	$65+j31$
$[Z_{L3}](\Omega)$	$80+j60$	$55+j41$	$60+j29$

	Phase Voltage (kV)			Sequence Voltage (kV)		VUF
	a	b	c	Positive	Negative	(%)
$[V_1]$	$6.27\angle 0.1$	$6.27\angle -120$	$6.27\angle 120$	$6.27\angle -0.14$	$0.01\angle 102$	$0.16\angle 102$
$[V_2]$	$5.90\angle 0.2$	$5.91\angle -121$	$5.95\angle 119$	$5.92\angle -0.88$	$0.05\angle 105$	$0.84\angle 106$
$[V_3]$	$5.95\angle 0.3$	$5.87\angle -121$	$5.90\angle 118$	$5.91\angle -0.75$	$0.04\angle 98$	$0.74\angle 98$

Table 3: Estimated voltages and voltage unbalance factor

	Phase Voltage (kV)			Sequence Voltage (kV)		VUF
	a	b	c	Positive	Negative	(%)
$[V_1]$	$6.27\angle 0$	$6.26\angle -120$	$6.26\angle 120$	$6.58\angle -0.2$	$0.01\angle 40$	$0.13\angle 40$
$[V_2]$	$5.75\angle -0.7$	$5.68\angle -123$	$5.73\angle 118$	$6.01\angle -1.8$	$0.06\angle 43$	$1.0\angle 37$
$[V_3]$	$5.58\angle -1.0$	$5.37\angle -124$	$5.45\angle 117$	$5.74\angle -2.6$	$0.11\angle 31$	$1.9\angle 33$

Table 4: Estimated voltages and voltage unbalance factor

8 Appendix 2

IEEE 14 bus Line Data

```
            |  From |  To    |    R      |    X      |      B/2   | X'mer
|
%           | Bus   | Bus    | Bus      |  pu       |       pu   |   TAP (a)
linedata14 =[1        2        0.01938    0.05917     0.0264          1
             1        5          0.05403    0.22304     0.0246          1
             2        3          0.04699    0.19797     0.0219          1
             2        4          0.05811    0.17632     0.0170          1
             2        5          0.05695    0.17388     0.0173          1
             3        4          0.06701    0.17103     0.0064          1
             4        5          0.01335    0.04211     0.0             1
             4        7          0.0        0.20912     0.0         0.978
             4        9          0.0        0.55618     0.0         0.969
             5        6          0.0        0.25202     0.0         0.932
             6       11          0.09498    0.19890     0.0             1
             6       12          0.12291    0.25581     0.0             1
             6       13          0.06615    0.13027     0.0             1
             7        8          0.0        0.17615     0.0             1
             7        9          0.0        0.11001     0.0             1
             9       10          0.03181    0.08450     0.0             1
             9       14          0.12711    0.27038     0.0             1
            10       11          0.08205    0.19207     0.0             1
            12       13          0.22092    0.19988     0.0             1
            13       14          0.17093    0.34802     0.0             1
```

9 Appendix 3

IEEE 4 bus system Data

The source is a 12.47 kV line-to-line infinite bus.

Closed Connections Load Data:

	Balanced	Unbalanced
Phase-1		
kW	1800	1275
Power Factor	0.9 lag	0.85 lag
Phase-2		
kW	1800	1800
Power Factor	0.9 lag	0.9 lag
Phase-3		
kW	1800	2375
Power Factor	0.9 lag	0.95 lag

Line Impedances

Phase impedance matrix:

$$zd = \begin{pmatrix} 0.4013 + 1.4133j & 0.0953 + 0.8515j & 0.0953 + 0.7266j \\ 0.0953 + 0.8515j & 0.4013 + 1.4133j & 0.0953 + 0.7802j \\ 0.0953 + 0.7266j & 0.0953 + 0.7802j & 0.4013 + 1.4133j \end{pmatrix} \quad \Omega/\text{mile}$$

Sequence impedances:

$$zd_{pos} = 0.306 + 0.6272j \quad \Omega/\text{mile}$$

$$zd_{zero} = 0.5919 + 2.9855j \quad \Omega/\text{mile}$$

Step-Down with Balanced Loading

Standard 30 degree connections are assumed for wye-delta and delta-wye banks

V1 = Vag for wye connections and Vab for delta connections
V2 = Vbg for wye connections and Vbc for delta connections
V3 = Vcg for wye connections and Vca for delta connections

Connection	Gr Y - Gr Y	Gr Y -D	Y - D	D - Gr Y	D - D	Open Gr.Y-D
Node-2						
V1	7107/-0.3	7113/-0.3	7112/-.03	12340/29.7	12339/29.7	6984/0.4
V2	7140/-120.3	7132/-120.3	7133/-120.4	12349/-90.4	12349/-90.4	7167/-121.7
V3	7121/119.6	7123/119.6	7124/119.6	12318/149.6	12321/149.6	7293/120.5
Node-3						
V1	2247.6/-3.7	3906/-3.5	3906/-3.4	2249/-33.7	3911/26.5	3701/-0.9
V2	2269/-123.5	3915/-123.6	3915/-123.6	2263/-153.4	3914/-93.6	4076/-126.5
V3	2256/116.4	3909/116.3	3909/116.3	2259/86.4	3905/146.4	3572/110.9
Node-4						
V1	1918/-9.1	3437/-7.8	3437/-7.8	1920/-39.1	3442/22.3	3384/-3.5
V2	2061/-128.3	3497/-129.3	3497/-129.3	2054/-158.3	3497/-99.4	3804.9/-130.2
V3	1981/110.9	3388/110.6	3388/110.6	1986/80.9	3384/140.7	3246/106.5
Current 1-2						
Ia	347.9/-34.9	334.8/-34.5	335.8/-34.7	335.0/-35.7	335.8/-34.7	380.9/-65.2
Ib	323.7/-154.2	335.4/-154.9	335.9/-154.6	331.8/-154.0	335.8/-154.6	387.4/-125.2
Ic	336.8/85.0	337.4/85.4	335.9/85.3	341.6/85.6	336.0/85.4	0
Current 3-4						
Ia	1042.8/-34.9	1006.6/-64.7	1006.6/-64.7	1041.9/-64.9	1006.7/-34.7	659.3/-65.2
Ib	970.2/-154.2	1006.7/175.4	1006.7/175.4	973.7/175.9	1006.7/-154.6	665.7/175.6
Ic	1009.6/85.0	1007.2/55.3	1007.2/55.3	1007.0/55.0	1007.2/85.4	670.5/54.8
Node 2						
Van			7116/-.03			
Vbn			7131/-120.3			
Vcn			7121/119.6			
Vng			3.6/169.5			

Step-Down with Unbalanced Loading

Standard 30 degree connections are assumed for wye-delta and delta-wye banks

V1 = Vag for wye connections and Vab for delta connections
V2 = Vbg for wye connections and Vbc for delta connections
V3 = Vcg for wye connections and Vca for delta connections

Connection	Gr Y - Gr Y	Gr Y -D	Y - D	D - Gr Y	D - D	Open Gr.Y-D
Node-2						
V1	7164/-0.1	7113/-0.2	7112/-0.2	12350/29.6	12341/29.8	6952/0.7
V2	7110/-120.2	7144/-120.4	7144/-120.4	12314/-90.4	12370/-90.5	7172/-122.0
V3	7082/119.3	7111/119.5	7112/119.5	12333/149.8	12302/149.5	7313/120.5
Node-3						
V1	2305/-2.3	3896/-2.8	3896/-2.8	2290/-32.4	3902/27.2	3632/0.1
V2	2255/-123.6	3972/-123.8	3972/-123.8	2261/-153.8	3972/-93.9	4121/-127.6
V3	2203/114.8	3875/115.7	3874/115.7	2214/85.2	3871/145.7	3450/108.9
Node-4						
V1	2175/-4.1	3425/-5.8	3425/-5.8	2157/-34.2	3431/24.3	3307/-1.5
V2	1930/-126.8	3646/-130.3	3646/-130.3	1936/-157.0	3647/-100.4	3907/-131.9
V3	1833/102.8	3298/108.6	3298/108.6	1849/73.4	3294/138.6	3073/103.1
Current 1-2						
Ia	230.1/-35.9	308.5/-41.5	309.8/-41.7	285.7/-27.6	361.7/-41.0	424.8/-73.8
Ib	345.7/-152.6	314.6/-145.5	315.5/-145.2	402.7/-149.6	283.5/-153.0	440.3/-118.5
Ic	455.1/84.7	389.0/85.9	387.2/85.9	349.1/74.4	366.5/93.2	0
Current 3-4						
Ia	689.7/-35.9	10083.8/-71.C	1083.8/-71.0	695.5/-66.0	1084/-41.0	735.2/-73.8
Ib	1036/-152.6	849.9/177.0	849.9/177.0	1033/177.1	849.7/-153.0	569.9/176.3
Ic	1364/84.7	1098.7/63.1	1098.7/63.1	1352/55.2	1099/93.2	762.0/61.5
Node 2						
Van			7116/-0.3			
Vbn			7142/-120.4			
Vcn			7109/119.6			
Vng			4.27/171.6			

For Estimation comparaison Y-Y connections is considered