POWER QUALITY IMPROVEMENT BY USING NON-LINEAR SLIDING MODE CONTROLLER WITH THE DYNAMIC VOLTAGE RESTORER

ALI BASIM MOHAMMED

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JUNE 2021

I dedicate this thesis to my parents. Without their understanding, support and most of all love, the completion of this work would not have been possible. Finally dedicate this thesis to the spirit of my daughter granular Rokaya which did not prohibit this day

ACKNOWLEDGEMENT

I thank the almighty ALLAH for his mercy and grace, which enabled me to complete this work.

Many people deserve my heartfelt thanks. I can only name some of those numerous people here. If you are one of the many more unnamed friends, you will know that I have valued your friendship and support during this study. Thank you.

I would like to express my sincerest thanks to Ts. Dr. Ahmad Fateh bin Mohamad Nor, Ir. Ts. Dr. Norfaiza binti Fuad, Ts. Dr. Danial bin Md Nor and Dr. Shibly Ahmed AL-Samarraie for giving me this opportunity to work under his supervision and for sharing his great knowledge and experience with me.

I express my deepest gratitude to my parents, my father and my mother for their encouragements throughout my education life, to my brothers and sister, to my wife for her support and effort, to my daughter Rawan and finally to the spirit of my daughter granular Rokaya which did not prohibit this day.

Their patience during my study, their love, care, and encouragement have given me the great inner strength to succeed. This work is dedicated to all of them.

ABSTRACT

The essential issue of the power system network is power quality. The bus voltage must be maintained as a sinusoidal waveform. Many disturbances affect the supply voltage, such as notching, transients, voltage sag/swell. The major power quality problems are voltage sag/swell and harmonics, which cause tripping or malfunctioning the equipment. The linear PID controller's output suffers from a high amplitude of error when the input signals are noisy. This thesis gives an effective solution to protect the sensitive loads from disturbances by utilizing the dynamic voltage restorer. It is defined as a controlled voltage source connected in series between the sensitive loads and the network through a series transformer to inject a proper voltage magnitude to keep the sensitive loads at a constant value. The two non-linear controllers employ a robust differentiator known as an approximate sliding mode differentiator (ACSMD) with a non-linear sliding variable named a terminal PID sliding variable (TPIDSV) or arctan PID sliding variable (ARTPIDSV). Simulation results were carried out by MATLAB/Simulink to investigate the performance of the proposed controllers. The performance improvement obtained from the proposed techniques upon comparison with the case study as a linear PID controller, the steady-state error 85%-99%, the total harmonic distortion 2%-51%, the voltage sag indices 85%-99% and the load voltage magnitude 0.2%-8.7% for voltage sag and 0.08%-2.9% for voltage swell in all cases. The results illustrated the DVR structure's ability to overcome the system's disturbances, maintaining the voltage magnitude of the sensitive loads at a constant value, minimizing the steady-state of error, and keeping the THD at an IEEE standard. The DVR system performance is evaluated by utilizing three types of voltage sag indices.

ABSTRAK

Isu penting rangkaian sistem kuasa adalah kualiti kuasa. Voltan bas mesti dikekalkan dalam bentuk gelombang sinusoidal. Pelbagai gangguan mempengaruhi voltan bekalan, seperti takik, transien, voltan lendut/kembang. Masalah kualiti kuasa utama ialah voltan lendut/kembang dan harmonik, yang menyebabkan peralatan tersekat atau tidak berfungsi. Output pengawal PID linier mengalami ralat amplitud tinggi ketika isyarat input berisik. Tesis ini memberikan penyelesaian yang berkesan untuk melindungi beban sensitif dari gangguan dengan menggunakan pemulih voltan dinamik. Ia didefinisikan sebagai sumber voltan terkawal yang dihubungkan secara bersiri antara beban sensitif dan rangkaian melalui transformer bersiri untuk menyuntikkan voltan yang betul untuk meletakkan beban sensitif pada nilai yang tetap. Kedua-dua pengawal tak linier menggunakan pembezaan kuat yang dikenali sebagai pembeza mod gelongsor anggaran (ACSMD) dengan pemboleh ubah gelongsor tak linier yang dinamakan pemboleh ubah gelongsor PID terminal (TPIDSV) atau pemboleh ubah gelongsor arctan PID (ARTPIDSV). Hasil simulasi dilakukan oleh MATLAB / Simulink untuk menyiasat prestasi pengawal yang dicadangkan. Peningkatan prestasi yang diperoleh dari teknik yang dicadangkan setelah dibandingkan dengan kajian kes sebagai pengawal PID linear, ralat keadaan stabil adalah 85% -99%, keseluruhan penyelewengan harmonik adalah 2% -51%, indeks voltan lendut adalah 85% -99% dan magnitud voltan beban 0.2% -8.7% untuk voltan lendut dan 0.08% -2.9% untuk voltan kembang dalam kesemua kes. Hasilnya menggambarkan kemampuan struktur DVR untuk mengatasi gangguan sistem, mengekalkan magnitud voltan beban sensitif pada nilai yang tetap, meminimumkan keadaan ralat stabil, dan menjaga THD pada tahap piawai IEEE. Prestasi sistem DVR dinilai dengan menggunakan tiga jenis indeks lendut voltan.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

$v_{L.dq}^{ref}$	-	The reference load voltage
$v_{D.dq}^{ref}$	-	The reference injected voltage
$v_{G.dq}$	-	The symmetrical components of the measured phase voltages in dq
$v_{D.\alpha\beta}^{ref}$	-	Reference injected voltage in αβ
$\lvert v_{G.m.1} \rvert$	-	The positive sequence component magnitude
φ_1	-	The positive sequence component angle
$v_{G.0}$	-	The zero component sequence
$V_{L.m}^{ref}$	-	The desired load voltage
$v_{G.a.2}$, $v_{G.b.2}$ and $v_{G.c.2}$	-	The negative sequence component of the instantaneous values of the three-phase
$v_{G.a.1}$, $v_{G.b.1}$, $v_{G.c.1}$	-	The difference transformed into instantaneous values
$V_{inj-reference}$	-	The reference injected voltage by DVR
${V_D}_a^{ref}, {V_D}_{,b}^{ref}, {V_D}_c^{ref}$	-	The reference compensating signals injected by the DVR
${V_D}_a^{ref}, {V_D}_b^{ref}$ and ${V_D}_c^{ref}$	-	Reference injected voltage in three phase
$\dot{V_{inj}}$	-	The second time derivative Vinj
$\lvert error_{dq0} \rvert$	-	The absolute error signal in dq0
$[sign(\sigma)]_{eq}$	-	The equivalent operator
$\dot{S}(e)$	-	The deravative sliding variable
THD_a, THD_b and, THD_c	-	The THD for phase a,b and c
I_L	-	Filter inductor current

I_g	-	The source current
R_f, L_f, C_f	-	The resistance, inductance and the capacitance of the filter
$V_{G,a}$, $V_{G,b}$, and $V_{G,c}$	-	The AC three phase system
$V_{G,d}$, $V_{G,q}$	-	The two-phase system by utilizing αβ /dq
$V_{G,\alpha}$, $V_{G,\beta}$	-	The two-phase system by utilizing abc/αβ
$V_{L,d}, V_{L,q}$ *and* $V_{L,0}$	-	The load voltage in dq0
V_d and V_q	-	The DC component of dq transform method
V_{inj}	-	The DVR injected voltage
V_{nom}	-	Nominal voltage
$V_{ref,d}, V_{ref,q}$ *and* $V_{ref,0}$	-	The reference voltage in dq0
$e_a(t)$ *and* $\dot{e}_a$	-	The actual error signal and error derivative
µF	-	Micro farad
AC	-	Alternating current
ACSMD	-	Approximate classical sliding mode differentiator
ANF	-	Adaptive notch filter
ARTPIDSV	-	Arctan PID sliding variable
CBEME	-	Computer and Business Equipment Manufacturers Association
CPD	-	Custom Power Device
CSA	-	Cuckoo search algorithm
DC	-	Direct current
de/dt	-	The deravative of error
DFIG	-	Doubly feed induction generator
DG	-	Distributed generation
dq0	-	The synchronous reference frame
DSC	-	Delayed Signal Cancellation
DSTATCOM	-	Distribution Static Synchronous Compensator
DVR	-	Dynamic Voltage Restorer
e	-	The error signal
EKF	-	Extended KF
EPRI	-	Electric Power Research Institute
E_{VS}	-	Voltage sag energy

f	-	The frequency
FACTS	-	Flexible AC transmission system
FBA	-	Flower pollination algorithm
FFT	-	Fast Fourier transform
FT	-	Fourier Transform
GOA	-	grasshopper optimization algorithm
GTO	-	Gate Turn-Off
GWO	-	Grey wolf optimizer
HFL-DVR	-	High-frequency-link-DVR
Hz	-	Hertz
IC	-	Incremental conductance algorithm
IDVR	-	Interline DVR
IEC	-	International electrotechnical commission
IEEE	-	Institute of electrical and electronics engineers
IGBTs	-	Insulated Gate Bipolar Transistors
IGCT	-	Integrated Gate Commutated Thyristor
IOFL	-	Input-Output feedback Linearization
ITAE	-	Integral time absolute error
ITIC	-	Information Technology Industry Council
KF	-	Kalman filtering
K_p, K_i and K_d	-	The Proportional, integral and Derivative gains
KVA	-	Kilo volt-ampere
kVAr	-	Kilo volte ampere reactive
KW	-	Kilo watt
LES	-	Least error squares
LPF	-	Low pass filter
MLIs		Multi-level inverters
MOSFETs	-	Metal Oxide Semiconductor Field Effect Transistors
MPPT	-	Maximum power point tracking
MVA	-	Mega volt-ampere
ns	-	Nano second
θ	-	The angle used in transformation

PBC	-	Passivity-based control
PCC	-	Point of common coupling
PF	-	Power factor
PI	-	Proportional-Integral
PID	-	Proportional integral derivative
PIDSV	-	PID sliding variable
PLL	-	Phase-locked loop
PQ	-	Power quality
PR	-	Proportional-resonant
PSD	-	Power spectral density
PSO	-	Particle swarm optimization
PU	-	Per unit
PV	-	The photovoltaic system
PVUR	-	Phase voltage unbalance rate
PWM	-	Pulse width modulation
R	-	The resistance
RMS	-	Root mean square
rpm	-	Root per minute
S(e)	-	The sliding variable
SA	-	Surge Arrester
SHE	-	Selective harmonic elimination
SMC	-	Sliding mode controller
SMES	-	Super-conducting Magnetic Energy Storage
SPWM	-	The sinusoidal pulse-width modulation
SRFT	-	Synchronous reference frame theory
SS	-	Detroit Edison sag score
SSTS	-	Solid-State Transfer switch
STF	-	Self-tuning filter
STFT	-	Short-time Fourier transform
SVC	-	Static Var Compensator
SVPWM	-	The space vector PWM
T	-	The time during the sag in a milliseconds
t	-	Time in second

T1	-	Transformer no.1
T2	-	Transformer no.2
T3	-	Transformer no.3
THD	-	Total harmonic distortion
THDv	-	The total harmonic distortion of voltage
TPIDSV	-	Terminal PIDSV
u(t)	-	The input of the differentiator
UPS	-	Uninterruptible Power Supply
USA	-	United states of america
UVE	-	Unit vector estimator
V	-	Volt
V_-	-	The negative voltage sequence
$V(t)$	-	Voltage magnitude at time t
V_+	-	The positive voltage sequence
V_A, V_B, and V_C	-	Voltages at phase A,B and C
V_A, V_B, and V_C	-	The RMS phase voltages
V_{avg}	-	The average phase voltage
VD	-	Voltage Disturbances
V_{DC}	-	The voltage of the DC storage
V_{dev}	-	The deviation from the average phase voltage
V_{DVR}	-	Voltage injection of the DVR
VSC	-	Voltage Source Converter
VSI	-	Voltage source inverter
VSLEI	-	Voltage sag lost energy index
W	-	The lost energy
WFFT	-	Windowed Fast Fourier Transform
WT	-	Wavelet Transform
σ	-	The observer sliding variable
Ω	-	Ohm
k and C	-	The gain be selected to ensure σ go to zero
v	-	The LPF output
x	-	Variable introduce in differentiator design
$y(t)$	-	The output of the differentiator

$\gamma(t)$	- The source of the steady state of error
$\delta(t)$	- The switching function
$\delta(t)V_{dc}$	- The control input
$\delta e(t)$ *and* $\delta\dot{e}$	- The uncertainty (noise) in the error signal and the error derivative
λ *, q and p*	- The gain be selected to ensure S go to zero
τ	- The time constant

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, power quality has received significant interest in the industrial distribution system. The disturbances like voltage sag/ swell, flicker, and harmonics are the common power quality problems [1]. In the meantime, power quality problems can be defined as a deviation of voltage, current, and frequency from its standard values in the power system [2,3]. The increased use of non-linear electronic control devices in electrical power systems could increase power quality deterioration. This means that more focus is needed by power industry agents [4]. However, from the perspective of industrial and commercial producers, a low power quality suffering in terms of money, time, and resources [2].

In terms of power quality, voltage sag and swell are core problems in the power systems at the distribution and transmission sides. Voltage sag or voltage dip can be described as the short duration of voltage drop in RMS (root mean square) from its standard voltage value, which is lower than the nominal voltage range of 0.1 to 0.9 per unit (PU) between half-cycle to 1 minute. Depending on the fault types, the voltage sags can either be balanced or unbalanced. However, they always have unpredictable scales. Voltage swell is characterized as the fast increment in RMS (root mean square) voltage value from the standard voltage over the ostensible esteem, extending from 1.1 to 1.8 PU for a half cycle to 1 minute. As a result, the vast burdens and energization of the capacitor banks will be turned off, causing voltage swell [2,5-8].

IEEE and IEC have introduced the standards for Power Quality (PQ). There are many types of custom power devices that could be applied to mitigate voltage sag and

REFERENCES

1. A. M. Rauf and V. Khadkikar, "An Enhanced Voltage Sag Compensation Scheme for Dynamic Voltage Restorer," *IEEE Transactions on Industrial Electronics.*, 62(5), pp. 2683–2692, 2015.
2. D. Francis and T. Thomas, "Mitigation of voltage sag and swell using dynamic voltage restorer," *2014 Annual International Conference on Emerging Research Areas: Magnetics, Machines and Drives (AICERA/iCMMD 2014)*, pp. 1-6. 2014
3. A. Moghassemi and S. Padmanaban, "Dynamic voltage restorer (DVR): A comprehensive review of topologies, power converters, control methods, and modified configurations," *Energies*, 13(6), pp. 1–44, 2020.
4. M. R. Alam, K. M. Muttaqi, and A. Bouzerdoum, "Characterizing Voltage Sags and Swells Using Three-Phase Voltage Ellipse Parameters," *IEEE Transactions on Industry Applications.*, 51(4), pp. 2780–2790, 2015.
5. R. Omar and N. A. Rahim, "Modeling and simulation for voltage sags/swells mitigation using dynamic voltage restorer (DVR)," *Australasian Universities Power Engineering Conference*, pp. 1–6, 2008.
6. J. Barros and E. Pérez, "Automatic detection and analysis of voltage events in power systems," *IEEE Transactions on Instrumentation and Measurement.*, 55(5), pp. 1487–1493, 2006.
7. A. A. Helal and M. H. Saied, "Dynamic voltage restorer adopting 150° conduction angle VSI," *2008 IEEE Electrical Power and Energy Conference - Energy Innovation.*, pp. 3–8, 2008.
8. A. de Almeida, L. Moreira, and J. Delgado, "Power quality problems and new solutions," *Renewable Energy and Power Quality Journal.*, 1(1), pp. 25–33, 2003.
9. Benachaiba, C. and Ferdi, B. "Voltage quality improvement using DVR," *Electrical Power Quality and Utilisation. Journal,* 14,pp.39-46,2008.
10. O. P. Taiwo, R. Tiako, and I. E. Davidson, "Voltage unbalance mitigation and

voltage profile enhancement in secondary distribution system using dynamic voltage restorer," *International Journal of Engineering Research in Africa*, 34(1), pp. 81–101, 2018.

11. J. G. Nielsen, F. Blaabjerg, and N. Mohan, "Control strategies for dynamic voltage restorer compensating voltage sags with phase jump," *IEEE Conference on Applied Power Electronics Conference and Exposition (APEC)* 2(1), pp. 1267–1273, 2001.
12. A. Meena, S. Islam, S. Anand, Y. Sonawane, and S. Tungare, "Design and control of single-phase dynamic voltage restorer," *Sādhanā* 42(8), pp. 1363–1375, 2017.
13. A. Bahrami, "*An Integrated Control Scheme For Dynamic Voltage Restorer To Limit Downstream Fault Currents*," Politecnico Di Milano, Ph.D Thesis. 2017.
14. Institute of Electrical and Electronics Engineers, *IEEE Approved Draft Guide for Voltage Sag Indices*. 2014.
15. I. Y. Chung, D. J. Won, S. Y. Park, S. Il Moon, and J. K. Park, "The DC link energy control method in dynamic voltage restorer system," *International Journal of Electrical Power & Energy Systems*, 25(7), pp. 525–531, 2003.
16. F. Martzloff, "Power quality work at the International electrotechnical commission,". *Proceedings, PQA'97 Europe, Stockholm,* pp. 1-7, 1997.
17. G. Ghosh, A. and Ledwich, "Power quality enhancement using custom power devices," *Springer Science. Business & media*: Springer.2012.
18. Electromagnetic compatibility (EMC) - Part 2: Environment - Section 5: Classification of electromagnetic environments. Basic EMC publication.
19. "IEC 61000-2-1: 1990, Electromagnetic Compatibility (EMC), Part 2, Environment,Section I: Description of Environment - Electromagnetic Environment for LowFrequency Conducted Disturbances and Signalling in Public Power Supply Systems. First Edition, 1990-05," 1990.
20. "IEEE 1159: 1995, IEEE Recommended Practices on Monitoring Electric Power Quality."
21. "IEEE c62.41: 1991, IEEE Recommended Practices on Surge Voltages in Low-Voltage AC Power Circuits."
22. "IEC 816: 1984, Guide on Methods of Measurement of Short Duration Transients on Low Voltage Power and Signal Lines."

23. "IEEE 519: 1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (ANSI)."

24. "IEC 61000-4-7: 1991, Electromagnetic Compatibility (EMC), Part 4: Limits, Section 7: General Guide on Harmonics and Inter-harmonics Measurements and Instrumentation for Supply Systems and Equipment Connected Thereto."

25. A.M.S.A. Fattah, "*Power Conditioning Using Dynamic Voltage Restorers Under Different Voltage Sag Types*," Cairo University, Egypt: Master's Thesis. 2015.

26. E. M. A. A. M. A. Aziz, "*Modeling and Simulation of Dynamic Voltage Restore in Power System*," Azhar University. Cairo: Master's Thesis.2012.

27. "IEEE Recommended Practice for Monitoring Electric Power Quality," vol. IEEE Stand, 1995.

28. Mangindaan, G. M. Ch and HP, M. A. M., "Control of Dynamic Voltage Restorer For Voltage Sag Mitigation," *4th International Conference on communication and network systems,* pp. 172-177, 2008.

29. M. H. J. Bollen, "Understanding power quality problems: Voltage sags and interruptions," *IEEE press,* pp. 1–543, 1999.

30. D. J. Won, S. J. Ahn, I. Y. Chung, J. M. Kim, and S. Il Moon, "A new definition of voltage sag duration considering the voltage tolerance curve," *2003 IEEE Bologna PowerTech - Conference Proceedings.*, 3(1), pp. 456–460, 2003.

31. E. Styvaktakis, M. H. J. Bollen, and I. Y. H. Gu, "Automatic classification of power system events using rms voltage measurements," *IEEE Power Engineering Society Transmission and Distribution Conference,* 2(1), pp. 824–829, 2002.

32. M. Öhrström and L. Söder, "A comparison of two methods used for voltage dip characterization," *2003 IEEE Bologna PowerTech-Conference Proceedings,* pp. 195–200, 2003.

33. E. E. P. Q. and R. Centre, "Voltage Sag Mitigation," 2012.

34. B. J. Quirl, B. K. Johnson, and H. L. Hess, "Mitigation of voltage sags with phase jump using a Dynamic Voltage Restorer," *2006 38th Annual North American Power Symposium.*, pp. 647–654, 2006.

35. A. Polycarpou "Power Quality and Voltage Sag Indices in Electrical Power Systems, in G. Romero, L. Martinez *Electrical Generation and Distribution Systems and Power Quality Disturbances*, Croatia: InTech. pp. 139-159. 2011.

36. B. Douglas, J., Gehl, S., and Barker, "The Future of Power Delivery in the 21st Century," *Electric Power Research Institute Journal.*, 24(2), pp. 18–18, 1999.
37. C. K. Duffey, and Stratford, R. P. Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems. *IEEE Transactions on Industry Applications*, 25(6), 1025-1034.1989.
38. A. Ghosh and G. Ledwich, "Compensation of Distribution System Voltage Using Dynamic Voltage Restorer (DVR)," *IEEE Power Engineering Review.*, 22(8), pp. 1030-1036, 2002.
39. K. R. Padiyar, *Facts Controllers in Power Transmission Distribution*, New Age International (P) Limited, Publishers. 2007.
40. C. Zhan, M. Barnes, V. K. Ramachandaramurthy, and N. Jenkins, "Dynamic voltage restorer with battery energy storage for voltage dip mitigation," *International Conference on Power Electronics and Variable Speed Drives*, pp. 360–365, 2000.
41. S. S. Choi, B. H. Li, and D. M. Vilathgamuwa, "Design and analysis of the inverter-side filter used in the dynamic voltage restorer," *IEEE Transactions on Power Delivery.*, 17(3), pp. 857–864, 2002.
42. M. A. El-Gammal, A. Y. Abou-Ghazala, and T. I. El-Shennawy, "Fifteen years of the dynamic voltage restorer: A literature review," *Australian Journal of Electrical and Electronics Engineering.*, 8(3), pp. 279–287, 2011.
43. C. Zhan., V.K. Ramachandaramurthy, A. Arulampalam, C. Fitzer, S. Kromlidis, M. Bames, and N. Jenkins, "Dynamic voltage restorer based on voltage-space-vector PWM control," *IEEE Transactions on Industry Applications.*, 37(6), pp. 1855–1863, 2001.
44. C. H. Rovai and A. Doorwar, "An overview of various control techniques of DVR," *2014 International Conference on Circuits, Power and Computing Technologie*, pp. 53–57, 2014.
45. S. Ali, Y. K. Chauhan, and B. Kumar, "Study & performance of DVR for voltage quality enhancement,"*2013 International Conference on Energy Efficient Technologies for Sustainability,* pp. 983–988, 2013.
46. M. Farhadi-Kangarlu, E. Babaei, and F. Blaabjerg, "A comprehensive review of dynamic voltage restorers," *International Journal of Electrical Power & Energy Systems.*, 92(1), pp. 136–155, 2017.

47. N. Kagan, E.L. Ferrari, N.M. Matsuo, S.X. Duarte, A. Sanommiya, J.L. Cavaretti, U.F. Castellano and A. Tenorio "Influence of RMS variation measurement protocols on electrical system performance indices for voltage sags and swells,"*International Conference on Harmonics and Quality of Power (ICHQP)*, 3(1), pp. 790–795, 2000.

48. M. Albu and G. T. Heydt, "On the use of RMS values in power quality assessment," *IEEE Transactions on Power Delivery,* 18(4), pp. 1586–1587, 2003.

49. M. Vilathgamuwa, A. A. D. Ranjith Perera, S. S. Choi, and K. J. Tseng, "Control of energy optimized Dynamic Voltage Restorer," *25th Annual Conference of the IEEE Industrial Electronics Society*,, pp. 873–878, 1999.

50. E. Pérez and J. Barros, "Voltage event detection and characterization methods: A comparative study," *2006 IEEE/PES Transmission & Distribution Conference and Exposition: Latin America*, pp. 1–6, 2006.

51. E. Perez and J. Barros, "A proposal for on-line detection and classification of voltage events in power systems," *IEEE Transactions on Power Delivery*, 23(4), pp. 2132–2138, 2008.

52. M. González, V. Cárdenas, and R. Álvarez, "Detection of sags, swells, and interruptions using the digital RMS method and Kalman filter with fast response," *IECON 2006-32nd Annual Conference on IEEE Industrial Electronics.*, pp. 2249–2254, 2006.

53. P. K. Dash and M. V. Chilukuri, "Hybrid S-Transform and Kalman Filtering Approach for Detection and Measurement of Short Duration Disturbances in Power Networks," *IEEE Transactions on Instrumentation and Measurement,* 53(2), pp. 588–596, 2004.

54. C. Meyer, R. W. De Doncker, Y. W. Li, and F. Blaabjerg, "Optimized control strategy for a medium-voltage DVR - Theoretical investigations and experimental results," *IEEE Transactions on Power Electronics.*, 23(6), pp. 2746–2754, 2008.

55. A. K. Sadigh and K. M. Smedley, "Review of voltage compensation methods in dynamic voltage restorer (DVR)," *IEEE Power & Energy Society General Meeting.*, pp. 1-8. 2012

56. M. R. Banaei, S. H. Hosseini, S. Khanmohamadi, and G. B. Gharehpetian, "Verification of a new energy control strategy for dynamic voltage restorer by

simulation," *The journal Simulation Modelling Practice and Theory*, 14(2), pp. 112–125, 2006.

57. K. Perera, D. Salomonsson, A. Atputharajah, and S. Alahakoon, "Automated control technique for a single phase dynamic voltage restorer," *2006 International Conference on Information and Automation*, pp. 63–68, 2006.

58. M. I. Marei, E. F. El-Saadany, and M. M. A. Salama, "A new approach to control DVR based on symmetrical components estimation," *IEEE Transactions on Power Delivery.*, 22(4), pp. 2017–2024, 2007.

59. D. A. Fernandes, S. R. Naidu, and J. A. E. Coura, "Instantaneous sequence-component resolution of 3-phase variables and its application to dynamic voltage restoration," *IEEE Transactions on Instrumentation and Measurement*, 58(8), pp. 2580–2587, 2009.

60. S. J. Lee, H. Kim, S. K. Sul, and F. Blaabjerg, "A novel control algorithm for static series compensators by use of PQR instantaneous power theory," *IEEE Transactions on Power Electronics.*, 19(3), pp. 814–827, 2004.

61. G. Chen, M. Zhu, and X. Cai, "Medium-voltage level dynamic voltage restorer compensation strategy by positive and negative sequence extractions in multiple reference frames," *IET Power Electroics.*, 7(7), pp. 1747–1758, 2014.

62. H. G. Jeong, K. B. Lee, S. Choi, and W. Choi, "Performance improvement of LCL-filter-based grid-connected inverters using PQR power transformation," *IEEE Transactions on Power Electronics.*, 25(5), pp. 1320–1330, 2010.

63. H. Kim, S. J. Lee, and S. K. Sul, "A calculation for the compensation voltages in dynamic voltage restorers by use of PQR power theory," *IEEE Applied Power Electronics Conference and Exposition*, 1(1), pp. 573–579, 2004.

64. E. Ebrahimzadeh, S. Farhangi, H. Iman-Eini, F. B. Ajaei, and R. Iravani, "Improved phasor estimation method for dynamic voltage restorer applications," *IEEE Transactions on Power Delivery*, 30(3), pp. 1467–1477, 2015.

65. A. L. Bukar, D. M. Said, B. Modu, A. Musa, A. K. Aliyu, A. Isah, I. Tijjani and J. G. Ringim, "An improvement of voltage quality in low voltage distribution system using dynamic voltage restorer," *ARPN Journal of Engineering and Applied Sciences.*, 10(20), pp. 9588–9595, 2015.

66. B. P. Ganthia, S. Mohanty, P. K. Rana, and P. K. Sahu, "Compensation of voltage sag using DVR with PI controller," *2016 International Conference on*

Electrical, Electronics, and Optimization Techniques (ICEEOT), pp. 2138–2142, 2016.

67. M. T. Ali, F. Abbas, A. Nadeem, M. Yaqoob, S. M. Malik, and M. J. Iqbal, "Effect of PI controller on efficiency of dynamic voltage restorer for compensation of voltage quality problems," *6th International Power Electronics and Motion Control Conference and Exposition*, pp. 1134–1139, 2014.
68. M. M. Silva, D. C., Silva, J. L., de Oliveira, J. G., Carmo, M. J., and Lanes, "Compensation of disturbances from the electrical network using the dynamic voltage restorer (DVR)," *2017 Brazilian Power Electronics Conference (COBEP).*, pp. 1–6, 2017.
69. B. Ren, X. Jiang, Z. Hongwei, S. Zongqiang, and L. Liwei, "Dynamic voltage restorer control based on RBF-PID," *2017 Chinese Automation Congress (CAC)*,pp. 7742–7745, 2017.
70. L. F. J. Meloni, Â. J. J. Rezek, and Ê. R. Ribeiro, "Small-signal modeling of a single-phase DVR for voltage sag mitigation," *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*,pp. 55–59, 2016.
71. Y. W. Li, F. Blaabjerg, D. M. Vilathgamuwa, and P. C. Loh, "Design and comparison of high performance stationary-frame controllers for DVR implementation," *IEEE Transactions on Power Electronics.*, 22(2), pp. 602–612, 2007.
72. Y. Wu, Z. Nie, and J. Zhu, "A single-phase400Hz Dynamic Voltage Restorer with PR control," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society.*, pp. 321–327, 2013.
73. V. Surendran, V. Srikanth, and T. G. Subhash Joshi, "Performance improvement of dynamic voltage restorer using proportional - Resonant controller," *2014 Power and Energy Systems: Towards Sustainable Energy*, pp. 1-5, 2014.
74. S. Guo and D. Liu, "Proportional-resonant based high-performance control strategy for voltage-quality in dynamic voltage restorer system," *The 2nd International Symposium on Power Electronics for Distributed Generation Systems*, 2(2), pp. 721–726, 2010.
75. Y. W. Li, D. M. Vilathgamuwa, F. Blaabjerg, and P. C. Loh, "A robust control scheme for medium-voltage-level DVR implementation," *IEEE Transactions*

on Industrial Electronics., 54(4), pp. 2249–2261, 2007.

76. R. Damaraju and S. V. N. L. Lalitha, "A fuzzy controller for compensation of voltage sag/swell problems using reduced rating dynamic voltage restorer," *Indian Journal of Science and Technology.*, 8(23),pp.1-6. 2015.

77. S. Solat, M. Moallem, and M. A. Latify, "A supervisory hierarchical fuzzy controller for dynamic voltage restorer (DVR)," *2015 23rd Iranian Conference on Electrical Engineering.*, 10(1), pp. 1694–1699, 2015.

78. K. Sandhya, A. J. Laxmi, and M. P. Soni, "Design of PI and Fuzzy Controllers for Dynamic Voltage Restorer (DVR)," *AASRI Procedia*, 2(1), pp. 149–155, 2012.

79. M. Trabelsi, H. Vahedi, H. Komurcugil, H. Abu-Rub, and K. Al-Haddad, "Low Complexity Model Predictive Control of PUC5 Based Dynamic Voltage Restorer," *018 IEEE 27th International Symposium on Industrial Electronics (ISIE)*, pp. 240–245, 2018.

80. M. Trabelsi, H. Komurcugil, S. S. Refaat, and H. Abu-Rub, "Model predictive control of packed U cells based transformerless single-phase dynamic voltage restorer," *2018 IEEE International Conference on Industrial Technology (ICIT)*, pp. 1926–1931, 2018.

81. C. Kumar and M. K. Mishra, "Predictive Voltage Control of Transformerless Dynamic Voltage Restorer," *IEEE Transactions on Industrial Electronics.*, 62(5), pp. 2693–2697, 2015.

82. J. Roldán-Pérez, A. García-Cerrada, J. L. Zamora-Macho, P. Roncero-Sánchez, and E. Acha, "Adaptive repetitive controller for a three-phase dynamic voltage restorer," *2011 International Conference on Power Engineering, Energy and Electrical Drives*, pp. 1-6. 2011

83. S. Guo, "Fast repetitive controller based low-voltage dynamic voltage restorer for voltage-quality issues in distribution system," *The 2nd International Symposium on Power Electronics for Distributed Generation Systems*, pp. 988–992, 2010.

84. R. Kapoor and M. Sushama, "Fault Current Control Using a Repetitive Controller Based DVR," *2015 Second International Conference on Advances in Computing and Communication Engineering*, pp. 224–227, 2015.

85. S. Y. Jeong, T. H. Nguyen, Q. A. Le, and D. C. Lee, "High-performance control of three-phase four- wire DVR systems using feedback linearization," *Journal*

of Power Electronics, 16(1), pp. 351–361, 2016.

86. G. Joós, S. Chen, and L. Lopes, "Closed-loop state variable control of dynamic voltage restorers with fast compensation characteristics," *the 2004 IEEE Industry Applications Conference, 2004. 39th IAS Annual Meeting.* 4(1), pp. 2252–2258, 2004.

87. M. González, V. Cárdenas, and G. Espinosa, "Advantages of the passivity based control in dynamic voltage restorers for power quality improvement," *The journal Simulation Modelling Practice and Theory*, 47(1), pp. 221–235, 2014.

88. G. V. N. Kumar and D. D. Chowdary, "DVR with sliding mode control to alleviate voltage sags on a distribution system for three phase short circuit fault," in *2008 IEEE Region 10 and the Third international Conference on Industrial and Information Systems*, pp. 1- 4. 2008.

89. A. Pandey, R. Agrawal, R. S. Mandloi, and B. Sarkar, "Sliding Mode Control of Dynamic Voltage Restorer by Using a New Adaptive Reaching Law," *Journal of The Institution of Engineers (India): Series B,* 98(6), pp. 579–589, 2017.

90. H. Komurcugil and S. Biricik, "Time-Varying and Constant Switching Frequency-Based Sliding-Mode Control Methods for Transformerless DVR Employing Half-Bridge VSI," *IEEE Transactions on Industrial Electronics,* 64(4), pp. 2570–2579, 2017.

91. M. S. Kasyap, A. Karthikeyan, B. V. Perumal, and C. Nagamani, "DSC filter based unit vector estimator for reference generation and control of dynamic voltage restorer," *2016 IEEE 7th Power India International Conference (PIICON)*,.pp. 1-6, 2016

92. M. C. Jiang and K. Y. Lu, "Analysis & design of a novel soft-switching single-phase dynamic voltage restorer," *2017 International Conference on Applied System Innovation (ICASI)*, pp. 861–864, 2017.

93. D. N. Katole, M. B. Daigavane, S. P. Gawande, and P. M. Daigavane, "Analysis, Design and Implementation of Single Phase SRF Controller for Dynamic Voltage Restorer under Distorted Supply Condition," *Energy Procedia*, 117, pp. 716–723, 2017.

94. S. Biricik, S. K. Khadem, S. Redif, and M. Basu, "Voltage distortion mitigation in a distributed generation-integrated weak utility network via a self-tuning

filter-based dynamic voltage restorer," *Electrical Engineering*, 100(3), pp. 1857–1867, 2018.

95. A. M. Massoud, S. Ahmed, P. N. Enjeti, and B. W. Williams, "Evaluation of a multilevel cascaded-type dynamic voltage restorer employing discontinuous space vector modulation," *IEEE Transactions on Industrial Electronics.*, 57(7), pp. 2398–2410, 2010.

96. C. Zhan, A. Arulampalam, and N. Jenkins, "Four-wire dynamic voltage restorer based on a three-dimensional voltage space vector PWM algorithm," *IEEE Transactions on Industrial Electronics.*,18(4), pp. 1093–1102, 2003.

97. H. Ding, S. Shuangyan, D. Xianzhong, and G. Jun, "A novel dynamic voltage restorer and its unbalanced control strategy based on space vector PWM," *International Journal of Electrical Power & Energy Systems.*, 24(9), pp. 693–699, 2002

98. Y. Zhao, "Design and implementation of inverter in dynamic voltage restorer based on selective harmonic elimination PWM," *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 2239–2244, 2008.

99. E. Babaei, M. F. Kangarlu, and M. Sabahi, "Dynamic voltage restorer based on multilevel inverter with adjustable dc-link voltage," *IET Power Electronics.*, 7(3), pp. 576–590, 2014.

100. F. A. L. Jowder, "Modeling and simulation of Dynamic Voltage Restorer (DVR) based on hysteresis voltage control," *IECON 2007-33rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 1726–1731, 2007.

101. S. H. Hosseini and M. Sabahi, "Three-phase DVR using a single-phase structure with combined hysteresis/dead-band control," *2006 CES/IEEE 5th International Power Electronics and Motion Control Conference.*, 3(1), pp. 1685–1689, 2007.

102. S. K. Spurgeon, "*Sliding mode control: theory and applications*," Boca Roton: Taylor & Francis., 1998.

103. N. Kassarwani, J. Ohri, and A. Singh, "Performance analysis of dynamic voltage restorer using modified sliding mode control," *International Journal of Electronics Letters.*, 7(1), pp. 25–39, 2019.

104. K. Jeyaraj, D. Durairaj, and A. I. S. Velusamy, "Development and performance analysis of PSO-optimized sliding mode controller–based dynamic voltage

restorer for power quality enhancement," *International Transactions on Electrical Energy Systems.*, 30(3), pp. 1–14, 2020.

105. J. Liu, "*Comparative Study of Differentiation and Integration Techniques for Feedback Control Systems*," Cleveland State University: Master's Thesis. 2002.

106. A. Basu, S. Mohanty, and R. Sharma, "Designing of the PID and FOPID controllers using conventional tuning techniques," *2016 International conference on inventive computation technologies (ICICT)*, pp. 1-6, 2016.

107. H. O. Bansal, R. Sharma, and P. R. Shreeraman, "PID Controller Tuning Techniques: A Review," *Journal of control engineering and technology,* 2(4), pp. 168-176, 2012.

108. K. J. A. and T. Hagglund, *PID controllers, Theory, design and tuning*.2nd Ed. Instrument Society of America. 1995.

109. D. M. Vilathgamuwa, H. M. Wijekoon, and S. S. Choi, "Interline dynamic voltage restorer: A novel and economical approach for multiline power quality compensation," *IEEE Transactions on Industry Applications*, 40(6), pp. 1678–1685, 2004.

110. M. Shahabadini and H. Iman-Eini, "Improving the Performance of a Cascaded H-Bridge-Based Interline Dynamic Voltage Restorer," *IEEE Transactions on Power Delivery.*, 31(3), pp. 1160–1167, 2016.

111. D. Vilathgamuwa, H.M. Wijekoon, and S.S. Choi, "A Novel Technique to Compensate Voltage Sags in Multiline Distribution System" *IEEE Transactions on Industrial Electronics*, 53(5), pp. 1603–1611, 2006.

112. M. Moradlou and H. R. Karshenas, "Design strategy for optimum rating selection of interline DVR," *IEEE Transactions on Power Delivery*, 26(1), pp. 242–249, 2011.

113. C. N. M. Ho and H. S. H. Chung, "Implementation and performance evaluation of a fast dynamic control scheme for capacitor-supported interline DVR," *IEEE Transactions on Power Electronics*, 25(8), pp. 1975–1988, 2010.

114. X. Liu and P. Li, "The effect of DVR on distribution system with distributed generation," *2007 International Conference on Electrical Machines and Systems (ICEMS)*, pp. 277–281, 2007.

115. W. El-Khattam, M. Elnady, and M. M. A. Salama, "Distributed Generation Impact on the Dynamic Voltage Restorer Rating," *2007 International*

Conference on Electrical Machines and Systems (ICEMS), pp. 595–599, 2003.

116. E. Babaei, F. M. Shahir, S. D. Tabrizi, and M. Sabahi, "Compensation of voltage sags and swells using photovoltaic source based DVR," *2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, pp. 903–906, 2017.

117. D. Divyalakshmi and N. P. Subramaniam, "Photovoltaic based DVR with Power Quality Detection using Wavelet Transform," *Energy Procedia*, 117, pp. 458–465, 2017.

118. S. S. Rao, P. S. R. Krishna, and S. Babu, "Mitigation of voltage sag, swell and THD using Dynamic Voltage Restorer with photovoltaic system," *2017 International Conference on Algorithms, Methodology, Models and Applications in Emerging Technologies (ICAMMAET),* pp. 1–7, 2017.

119. V. K. Amalorpavaraj, R. A. J., Kaliannan, P., Padmanaban, S.Subramaniam, U. and Ramachandaramurthy, "Improved Fault Ride Through Capability in DFIG Based Wind Turbines Using Dynamic Voltage Restorer With Combined Feed-Forward and Feed-Back Control," *IEEE Access*, 5, pp. 20494-20503. 2017.

120. A. Rini Ann Jerin, N. Prabaharan, K. Palanisamy, and S. Umashankar, "FRT Capability in DFIG based Wind Turbines using DVR with Combined Feed-Forward and Feed-Back Control," *Energy Procedia*, 138, pp. 1184–1189, 2017.

121. D. D. Chowdary and G.V.N. Kumar, "Restoration of single phase distribution system voltage under fault conditions with DVR using sliding mode control," *Indian Journal of Science and Technology,* 5(1), pp. 1–5, 2008.

122. D. D. Chowdary and G. V. N. Kumar, "Mitigation of voltage sags in a distribution system due to three phase to ground fault using DVR," *Indian Journal of Engineering and Materials Sciences,* 17(2), pp. 113–122, 2010.

123. J. F. Pires, V. F. Guerreiro, M. and Silva, "Dynamic Voltage Restorer Using a Multilevel Converter with a Novel Cell Structure," *2011 IEEE EUROCON-International Conference on Computer as a Tool,* pp. 1–4, 2011

124. S. Biricik, H. Komurcugil, and M. Basu, "Sliding mode control strategy for three-phase DVR employing twelve-switch voltage source converter," *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, pp.

921–926, 2015.

125. S. Biricik and H. Komurcugil, “Optimized Sliding Mode Control to Maximize Existence Region for Single-Phase Dynamic Voltage Restorers,” *IEEE Transactions on Industrial Informatics,* 12(4), pp. 1486–1497, 2016.

126. L. P. Vasudevan and V. Prasad, “Performance enhancement of a dynamic voltage restorer,” *Turkish Journal of Electrical Engineering & Computer Sciences*, 25(3), pp. 2293–2307, 2017.

127. A. J. Sguarezi Filho, D. A. Fernandes, J. H. Suárez, F. F. Costa, and J. A. T. Altuna, “Recursive Least Squares and Sliding Mode Control for Voltage Compensation of Three-Phase Loads,” *Journal of Control, Automation and Electrical Systems*, 26(6), pp. 769–777, 2018.

128. S. Biricik, H. Komurcugil, N. D. Tuyen, and M. Basu, “Protection of sensitive loads using sliding mode controlled three-phase DVR with adaptive notch filter,” *IEEE Transactions on Industrial Electronics*, 66(7), pp. 5465–5475, 2019.

129. H. Toodeji and S. H. Fathi, “Cost reduction and control system improvement in electrical arc furnace using DVR,” *2009 4th IEEE Conference on Industrial Electronics and Applications*, pp. 211–215, 2009.

130. A. Y. Goharrizi, S. H. Hosseini, M. Sabahi, and G. B. Gharehpetian, “Three-phase HFL-DVR with independently controlled phases,” *IEEE Transactions on Power Electronics*, 27(4), pp. 1706–1718, 2012.

131. F. E. Tuladhar, L. R. and Villaseca, “Dynamic voltage restorer with active disturbance rejection control,” *2014 North American Power Symposium (NAPS)*, pp. 1–6, 2014.

132. A. I. Omar, S. H. E. Abdel Aleem, E. E. A. El-Zahab, M. Algablawy, and Z. M. Ali, “An improved approach for robust control of dynamic voltage restorer and power quality enhancement using grasshopper optimization algorithm,” *ISA transactions*, 95, pp.110–129, 2019.

133. M. González, V. Cárdenas, L. Morán, and J. Espinoza, “Selecting between linear and nonlinear control in a dynamic voltage restorer,” *2008 IEEE Power Electronics Specialists Conference*, pp. 3867–3872, 2008.

134. M. Sarhangzadeh, S. H. Hosseini, M. B. B. Sharifian, G. B. Gharehpetian, and O. Sarhangzadeh, “Dynamic analysis of DVR implementation based on nonlinear control by IOFL,” *2011 24th Canadian Conference on Electrical and*

Computer Engineering (CCECE), pp. 000264–000269, 2011.

135. P. Chawla, R. Khanna, and A. Singh, "Fuzzy logic control for DVR to counter voltage sag on a distribution network," *Proceedings of the world congress on Engineering*, pp. 1321–1326, 2011.

136. N. H. Saad "Backstepping Nonlinear Control Strategy for Dynamic Voltage Restorer Using Multilevel Inverter," *The 16th International Middle East Power Systems Conference (MEPCON'14)*, pp. 2–6, 2014.

137. Y. Shtessel, C. Edwards, L. Fridman, and A. Levant, *Sliding mode control and observation*. New York: Springer.2014.

138. M. S. Utkin, Vadim, Jürgen Guldner, *Sliding mode control in electro-mechanical systems*, 34th ed. CRC press. 1999.

139. S. A. Al-Samarraie and M. Hussein Mishary Me, "A Chattering Free Sliding Mode Observer with Application to DC Motor Speed Control," *2018 Third Scientific Conference of Electrical Engineering (SCEE)*, pp. 259–264, 2018.

140. M. Zhihong, A. P. Paplinski, and H. R. Wu, "A Robust Mimo Terminal Sliding Mode Control Scheme For Rigid Robotic Manipulators," *IEEE Transactions on Automatic Control*, 39(12), pp. 2464–2469, 1994.

141. X. Zhihong, M. and Yu, "Adaptive terminal sliding mode tracking control for rigid robotic manipulators with uncertain dynamics," *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing,* 40(3), pp. 493-502., 1997.

142. S.T. Venkataraman and S. Gulati, Control of Nonlinear Systems Using Terminal Sliding Modes. *Journal of Dynamic Systems, Measurement, and Control*, 115(3), 1993

143. L. Fridman, J. A. Moreno, B. Bandyopadhyay, and S. Kamal, *Recent Advances in Sliding Modes: From Control to Intelligent Mechatronics*, Switzerland: Springer. 2015.

144. R. Fridman, L., Moreno, J. and Iriarte, "Sliding modes after the first decade of the 21st century," *Lecture Notes in Control and Information Sciences*, 412, pp. 113–149, 2011.

145. J. Han and C. Moraga, "The influence of the sigmoid function parameters on the speed of backpropagation learning," *International Workshop on Artificial Neural Networks*, 930, pp. 195–201, 1995.

146. Wikipedia, "https://en.wikipedia.org/wiki/Sigmoid_function." .

147. M. Esmaeili, H. Shayeghi, K. Valipour, A. Safari, and F. Sedaghati, "Power quality improvement of multimicrogrid using improved custom power device called as distributed power condition controller," *International Transactions on Electrical Energy Systems.*, 30(3), pp. 1–16, 2020.

148. Quality of power: Challenges to the Power quality of modern electricity grids, December, 12, 2015. "https://sudaspace.wordpress.com/category/quality-of-power".