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A Novel Control Algorithm for Self Adjusting Dynamic Voltage Stabilization Scheme

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***Abstract*—The paper presents a novel FACTS based Dynamic Voltage Stabilization Scheme (DVSS) for Distribution/Utilization Grid systems. The FACTS device is controlled by using multi loop error driven dynamic control strategies. In order to do this Matlab/Simulink/Simpower Software with GUI interface has been used for all digital simulation models of the all sub system components, DVSS, and the control algorithms. The proposed FACTS-DVSS is controlled by using a multi-loop decoupled controller scheme with either PI, fuzzy logic or sliding mode controllers. The novel FACTS device with flexible controllers is validated under system and load excursions and is proven to be effective in enhancing power quality and electric energy utilization as well as effective dynamic voltage stabilization, transient voltage excursions and inrush current conditions.**

***Index Terms*—Dynamic voltage stabilization, distribution systems, PI, fuzzy logic control, sliding mode control.**

I. INTRODUCTION

As the electrical power generation stations with different types and distributed generation are put into service; Efficient Energy Utilization and Power Quality issues have been one of the major topics in power distribution systems [1]. The combination of linear, nonlinear, and motor type loads have unpredictable effects on the power distribution systems [2]. Since the switching instances are not scheduled or known events, they have to be either estimated for a good power management or necessary precautions must be taken to eliminate the switched load effects on the distribution side. Power quality problems mostly stem from loads connected to electric supply systems [3], [4].

While linear type loads produce currents proportional to the voltage, the load current is not proportional to the instantaneous voltage in nonlinear loads such as personal computers, printers, UPS, adjustable speed drives, electronic lighting ballasts, ferromagnetic type devices, DC motor drives and arcing equipment. Besides, equipment overheating, transformer derating, failure of sensitive electronic equipment, interference with telecommunication systems, flickering of fluorescent lights, erratic operation of circuit breakers and relays, conductor overheating, and increased RMS current can be considered as additional problems caused by harmonic components [5]. Standards have been developed to deal with the problems originating from harmonics. The European harmonic standard, IEC-555 and the IEEE standard 519-1992 specify harmonic current limits and recommend control methods for power systems. Different approaches have been studied in literature to mitigate the main power quality problems [6], [7].

The harmonic distortion in power systems can be reduced using passive or active filters. Since the passive filters have undesirable series and parallel resonances, large and heavy sizes, high losses, and effects on certain harmonic components only, they have been replaced by active filters during last decades [8]. Besides, active filters are cost effective for large nonlinear loads, and they can be implemented in power systems as hybrid active filters [9]. Various control techniques with special methodologies have been used considering linear and nonlinear properties of power systems [10]–[12]. Depending on the operational requirements, applications, and system configuration, the type and methodologies of the controllers show viability [7].

This paper presents a novel FACTS based dynamic voltage stabilization scheme (DVSS) with newly modified fuzzy logic and sliding mode flexible control strategies driven by the unified error signal (UES) from a multi loop dynamic error controller scheme. Both DVSS and UES are modified to meet the requirements for voltage disturbance compensation and current harmonics of distribution/ utilization systems operating under variable conditions. A complete simulation model of the proposed system is developed in Matlab/Simulink/Simpower Sofware Environment using operational dynamic blocks available in Simulink library. The system is simulated with different control strategies under variable operating conditions for comparison. The controllers and the control strategies are developed to have the novel FACTS DVSS be operated for power factor and efficiency improvement, energy losses reduction, power quality, and less current harmonics.

The system simulation with proposed control techniques under variable operating conditions are preceded the discussion of the results and conclusions.

II. RADIAL STUDY SYSTEM

The proposed FACTS based dynamic voltage stabilization scheme (DVSS) is simulated for the power distribution system shown in Fig. 1 and Fig. 2 without and

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with the novel DVSS, respectively. The sample study system is a typical 25 kV, 10 km distribution system with a hybrid load consisting of linear load at power factor 0.85 (lagging), a motorized load and a nonlinear converter type load at the end of the feeder. Two step-down transformers are used at the main feeder. The numerical values of the system parameters are given in Appendix.

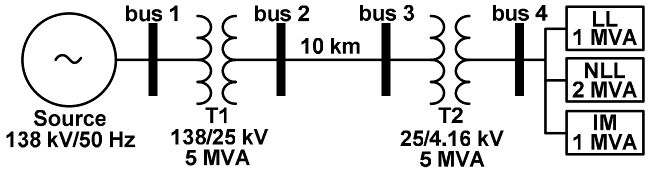


Fig. 1. Single-line diagram of the power system without the FACTS DVSS.

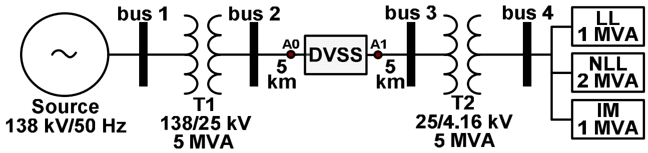


Fig. 2. Single-line diagram of the power system with Mid-Way FACTS DVSS.

The hybrid load connected at the end of the distribution feeder is a combination of residential, commercial and industrial loads. Figure 3 shows basic three phase wiring diagrams of the loads. The linear type loads are represented by resistances and inductors connected in parallel for each phase. Induction motors are considered as the motor type loads and they are represented by d-q equations for the simulation modelling. With the advancements in power electronics, most of the industrial and commercial loads are using switched power converters as the main actuators in their controlled circuitry. It is well known that switched type loads cause current discontinuities, voltage distortions and generate harmonics. Therefore, the switched loads are considered as the nonlinear type loads. The nonlinear load used in this study is modelled by a controlled rectifier fed circuitry consisting of a variable resistor connected in parallel with a capacitor.

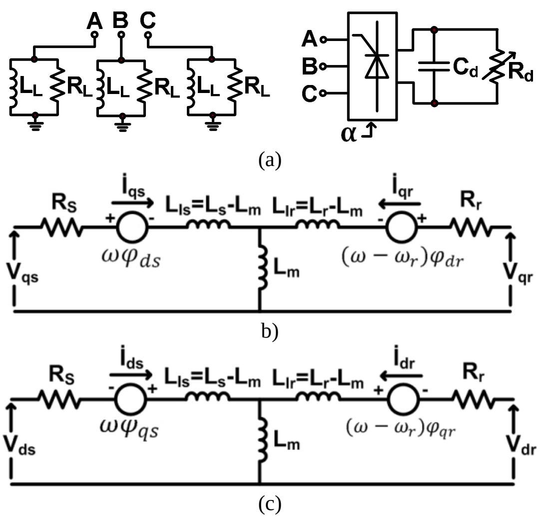


Fig. 3. The system loads types. a) AC linear type load, b) nonlinear converter load, c) dynamic or d-q equivalent circuit of an AC induction machine load.

The power distribution system is simulated and analysed for performance and power quality issues under various operating conditions of the hybrid load. The parallel RL load is not going to be discussed here because of its simplicity. The modelling of three phase induction motors using Park's transformation methods have been well studied in literature [13] therefore it will not be repeated here. However, the modelling of nonlinear loads used in this study should be explained, because if it is not a certain type device, the structure and properties of a nonlinear load may vary resulting in a different dynamic model.

The nonlinear type load used in this study is depicted in Fig. 3(b). A controlled DC converter is feeding a variable dynamic (temporal) resistor connected in parallel with a capacitor. The variable resistor R_d, has a characteristic represented as in (1)

$$R_d = R_0 + R_1 \sin^2 \mu_{o2} t, \tag{1}$$

where R_0 is a frequency independent component and represents the linear behaviour of R_d. R_1 is the peak value of variable component of R_d and μ_{o2} is the nonlinear load frequency. The load switching is done by triggering the AC/DC converter depending on thyristor firing angle $\sim$, which is represented as

$$\sim = \sim_0 + \sim_1 \sin^2 \mu_{o1} t, \tag{2}$$

where $\sim_0$ and $\sim_1$ are the minimum and the peak values of the firing angle $\sim$, respectively. μ_{o1} is the applied voltage frequency. The switching effects of the AC/DC converter on the load result in discontinuity current waveforms and yield harmonic components in AC current. Therefore, the current drawn from the power system becomes highly reactive.

In order to reduce the harmonic components and reactive power dissipation in power distribution feeder, an active filter with the abilities of harmonic elimination and voltage stabilizing should be designed and employed and a dynamic voltage stabilization scheme (DVSS) is adapted from [14] and modified to be used with the distribution system studied here. The modified novel DVSS comprises both shunt and series compensations used to increase power system capacity.

III. Modified Novel Dynamic Stabilization Scheme (DVSS)

In order to eliminate unwanted harmonic effects and voltage distortions, a power conditioning device is required in power systems. The power conditioner device proposed in this study is a unified hybrid dynamic stabilization scheme consisting of both series and shunt compensation as the passive filter components are in series and active filter components are in shunt as shown in Fig. 4. Due to its positive effects on line voltage stabilization, it is called dynamic voltage stabilization scheme and connected at the midpoint of the distribution line.

C_{S1} and C_{S2} in Fig. 4 are the passive components of the series compensation, which is adapted into the power line to increase power transmission capacity. The series compensation is also used to reduce the effective power losses and to improve line stability limits [15], [16].

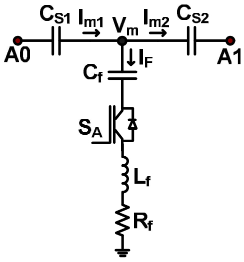


Fig. 4. A schematic diagram of the proposed Mid-Way FACTS DVSS topology.

In Fig. 4 V_m is the midpoint RMS voltage of the distribution line. C_f, L_f, and R_f are the capacitor, inductor, and resistor of the shunt compensation, respectively. S_A is the controlled semiconductor switch. The second contribution of this study is design of proper controller for the switch S_A for the active shunt compensation in DVSS, which is used to reduce the active and reactive power losses to ensure sufficient voltage levels. A combination of active shunt and series compensation strategy is implemented in the power systems to decrease drawbacks of both passive and active compensations in this study. The selected parameters of the proposed FACTS-Modulated Filter/Compensator DVSS are listed in Appendix.

The selected values of the Modulated Filter/Capacitor Compensation Scheme components are an important task in designing the power filters. The use of a small capacitor causes a large overvoltage across its terminals and does not compensate sufficiently while the leakage inductance results in a lagging current drawn from the AC bus. On the contrary, a large capacitor induces low voltage and causes overcompensation of the reactive power demand. Therefore a leading current might be drawn from the AC system [9].

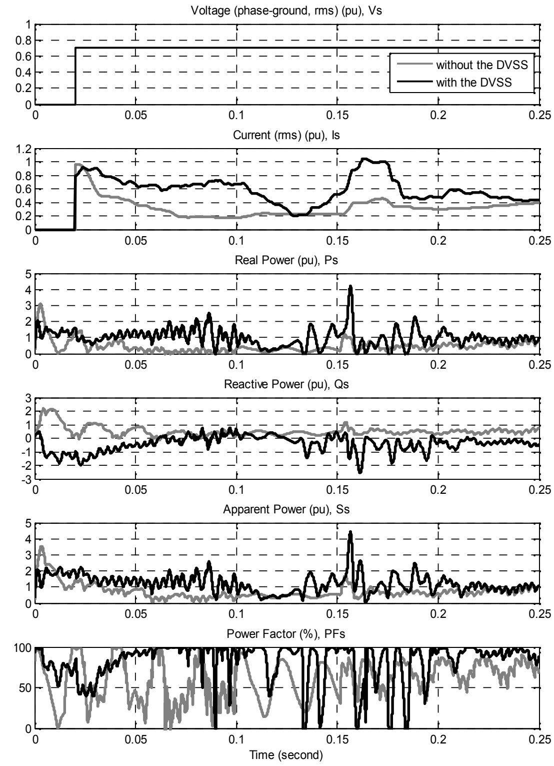
In order to increase the power transmission capacity of the system by reducing the effective line reactance, the series capacitors (C_{S1}, C_{S2}) are added in the distribution line. In addition to the series capacitors, an inductance (L_f) is connected in series with shunt capacitor (C_f) to limit the inrush current. Consequently, passive and active compensators, which comprise series capacitors (C_{S1}, C_{S2}), shunt capacitor (C_f), inductance (L_f) and resistance (R_f) provide the required capacitive power (VAr) for a power system with low frequency harmonics. The controlled compensation systems and fast switching devices are used to control both active and reactive power efficiently.

IV. FLEXIBLE DVSS CONTROL STRATEGY

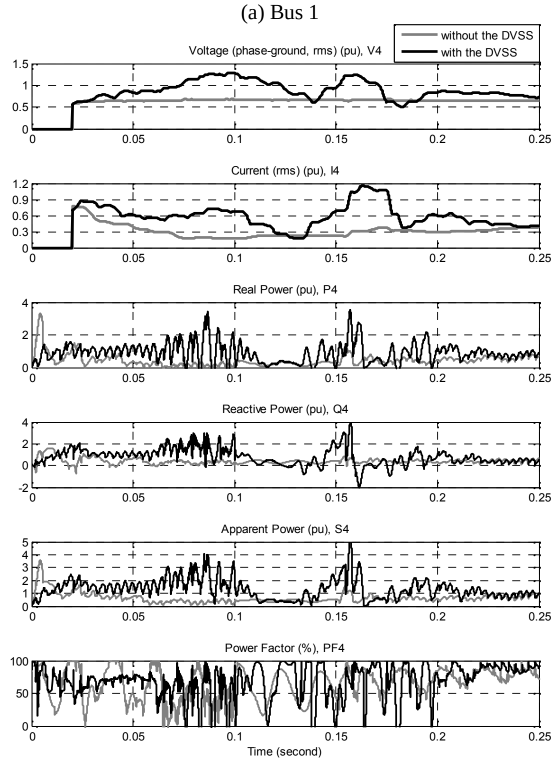
An effective controller requires many parameters and variables to be taken into account. With assumptions and ignorance of the variations in other variables rather than the one is controlled weakens the control purpose and efficiency. When controlling the midpoint voltage level in a power system, the current carrying capacity and power transmission limits of the line must be taken into the account besides the voltage controlled level. Therefore the currents entering and leaving the line midpoint where the shunt compensation part of the DVSS is connected are considered as the additional driving variables of the DVSS control algorithm beside the control voltage of the midpoint. In order to generate a multi-variable based control signal a multi loop error driven algorithm is adopted from [12] is used here with the proposed control algorithms.

V. DIGITAL SIMULATION AND RESULTS

The performance of the FACTS DVSS device is evaluated for a case using dynamic control strategies with different controllers such as proportional plus integral (PI), fuzzy logic controller (FLC), and sliding mode controller (SMC). The system simulation is done for duration of 0.25 sec with a sampling rate of 50 μs in Matlab/Simulink/ Simpower Software Environment.



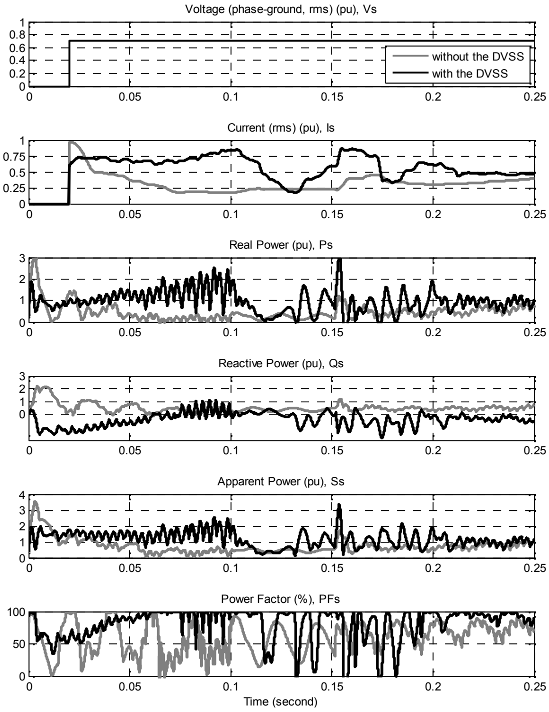
(a) Bus 1



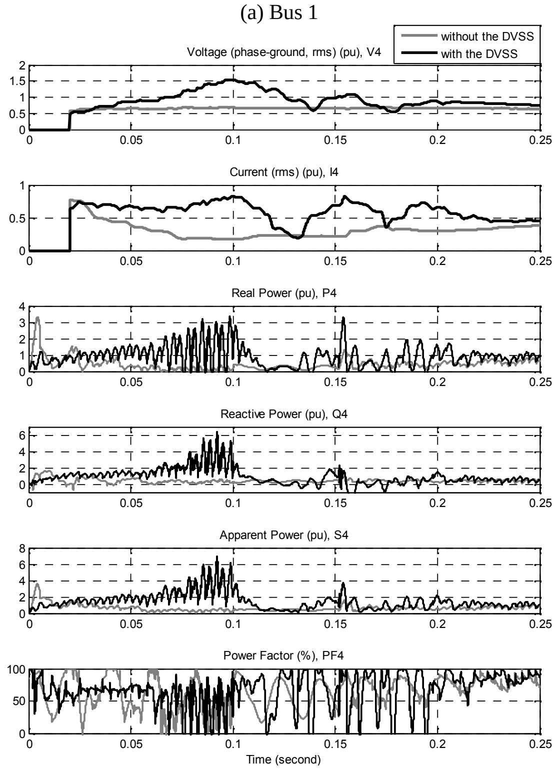
(b) Bus 4

Fig. 5. Dynamic responses of the sample study system without and with the DVSS (PI).

The system parameters are given in Appendix. The novel FACTS-DVSS device is used to stabilize the voltage at the key feeder interface buses, and enhance the power transfer capability of the distribution feeder to decrease the feeder congestion problems, and improve the power quality.



(a) Bus 1



(b) Bus 4

Fig. 6. Dynamic responses of the sample study system without and with the DVSS (FLC).

The dynamic performance of the novel FACTS-DVSS device was tested under the following case:

Case (Hybrid Electric Load Changes):

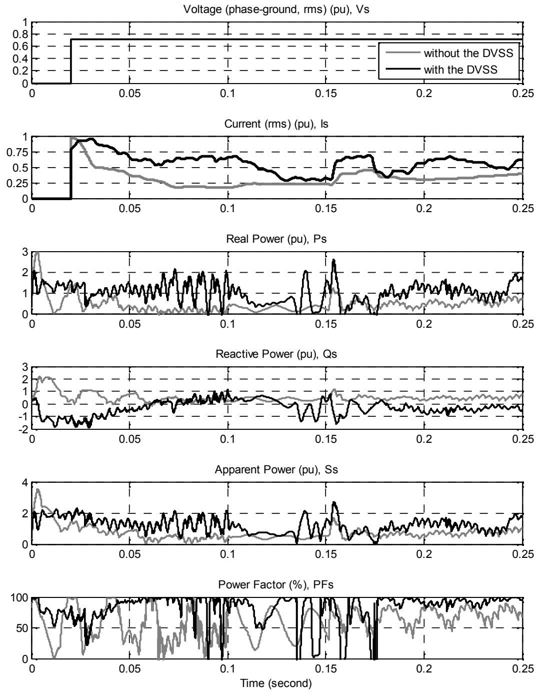
1) At t = 0.05 seconds, AC linear type load at bus 4 was removed for a duration of 0.05 seconds;

2) At t = 0.1 seconds, nonlinear converter load at bus 4 was removed for a duration of 0.05 seconds;

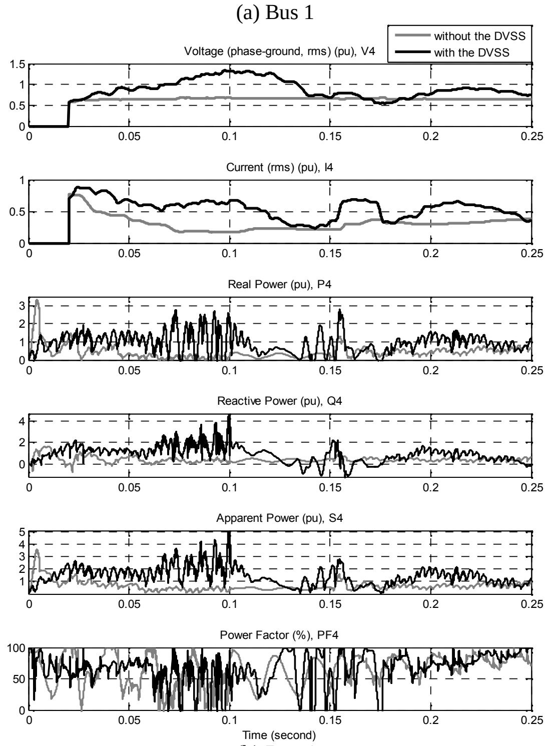
3) At t = 0.1 seconds, AC induction motor load torque (T_m) was applied to the motor with $\Delta T = -50\%$ for a duration of 0.05 seconds;

4) At t = 0.15 seconds, AC induction motor load torque (T_m) was applied to the motor with $\Delta T = +50\%$ for a duration of 0.05 seconds;

5) At t = 0.2 seconds, the system was reset to initial state.



(a) Bus 1



(b) Bus 4

Fig. 7. Dynamic responses of the sample study system without and with the DVSS (SMC).

The dynamic responses of voltage, current, real power, reactive power, apparent power and power factor at the Bus 1 and Bus 4 both without and with the DVSS compensation are shown in Fig. 5–Fig. 7..

TABLE I. VOLTAGE AND CURRENT HARMONICS IN THE SAMPLE STUDY SYSTEM WITHOUT AND WITH THE DVSS.

		Voltage harmonics				Current harmonics			
Bus no.	Controller	THD (%)	3rd (%)	5th (%)	7th (%)	THD (%)	3rd (%)	5th (%)	7th (%)
1	PI	0.05	0.02	0.02	0.01	11.19	8.41	5.53	1.06
	FLC	0.05	0.00	0.02	0.01	13.98	1.28	4.68	2.41
	SMC	0.05	0.01	0.01	0.00	12.47	4.51	1.86	1.13
	Without	0.03	0.00	0.02	0.01	18.97	2.77	8.29	2.29
4	PI	6.88	1.53	4.55	1.12	13.67	9.96	7.10	0.78
	FLC	7.07	0.98	2.95	2.72	16.03	2.26	5.02	2.32
	SMC	6.15	1.49	2.15	1.60	15.18	5.32	2.44	2.26
	Without	7.63	0.65	4.82	1.63	17.78	0.44	7.55	2.01

TABLE II. METER READINGS OF THE SYSTEM PARAMETERS AT THE BUSES 1 AND 4.

	DVSS	Controller	Phase Voltage	Current	Real Power	Reactive Power	Apparent Power	Power Factor
Bus 1	**ON**	**PI**	0.6507	0.5481	1.002	-0.4228	1.225	0.8194
		FLC	0.6507	0.5448	0.9759	-0.3750	1.193	0.80.33
		SMC	0.6506	0.5289	1.004	-0.3184	1.215	0.8070
	OFF	**Without**	0.6503	0.2999	0.4498	0.5139	0.7253	0.6064
Bus 4	**ON**	**PI**	0.8267	0.5479	0.8912	0.8059	1.338	0.6692
		FLC	0.8560	0.5500	0.9167	0.9108	1.444	0.6526
		SMC	0.8282	0.5097	0.9259	0.8980	1.427	0.6429
	OFF	**Without**	0.6025	0.2862	0.4379	0.4084	0.6437	0.6493

The digital simulation results presented below indicate that the DVSS is capable of reducing voltage and current harmonics as required by the regulations. Comparisons of harmonics at the bus without and with the novel DVSS device are shown in Fig. 5–Fig. 7. Voltage and current harmonic analysis in terms of the total harmonic distortion (THD) and the magnitudes of the dominant lower order harmonics are given in Table I and Table II.

The line current mainly includes 3rd, 5th and 7th harmonics components. The weights of these components changes depending on nonlinear load type, converter type and load switching in various subsystems. Some loads increase 3rd harmonics while some others cause the 5th or 7th harmonics to be increased. Without the DVSS compensation the magnitudes of some of the individual harmonic components become smaller than when it is with the DVSS. Since the DVSS is used to reduce THD in line current rather than a specific harmonic component, it is observed that THD has been reduced with the DVSS when some of the individual harmonic components tend to increase.Table I shows the reduced THD values with the DVSS utilizing different type controllers. Table I is also used to compare the effects of the controllers in reducing THD when they are used with the DVSS. The meter readings of the system parameters at Bus 1 and Bus 4 are tabulated in Table II.

From the results given in Table II, it is clear that the voltage, current, power and power factor have been noticeably increased at the buses tested under different control strategies (PI, FLC, SMC) in the distribution system

VI. CONCLUSIONS

In this paper, a novel Dynamic Voltage Stabilization Scheme developed by the Second Author for dynamic voltage stabilization/regulation and power quality enhancement. The novel DVSS-Modulated Filter/ Compensator is controlled using multi-loop dynamic error driven control strategies using Classical PI, Fuzzy and sliding mode controllers developed for distribution/ utilization systems.

The novel DVSS-FACTS device, DVSS, with controller is simulated by using Matlab-Simulink on a sample radial power distribution system by focusing on power quality, harmonics and voltage distortion problems. The harmonic-content in line current produce additional feeder losses. The negative influence of harmonics on the AC system active power is reduced by the novel FACTS-DVSS using fuzzy logic controller. The new FACTS-DVSS device with dynamic fuzzy logic control strategies can also be used to improve power factor and reduce energy losses while ensuring feeder capacity improvement and efficient energy utilization. Enhanced power quality and reduced current harmonics for hybrid loads consisting of residential, commercial and industrial loads are also ensured by the proposed FACTS-DVSS device and controllers, which are PI, FLC, and SMC.

The digital simulation results show considerable improvements in power quality in terms of reduced THD, improved power factor, reduced voltage transients/voltage sags and limited inrush currents. A Quad-Loops dynamic error Control Scheme enables the proposed three controller options to account for variations in feeder currents as well as interface bus voltage error so that the novel FACTS-DVSS is more effective in compensating for power system voltage and current excursions.

The use of this control strategy enables the control system to consider any changes in load voltage and load current to generate the required dynamic control action. The multi-loop control strategy can be further modified to enhance power quality, voltage stabilization, loss reduction in the power system, and hybrid renewable green energy systems. The novel DVSS-FACTS device is being validated for Hybrid Renewable Energy-Micro/Smart Grid applications and in Loss reduction in Congested AC Transmission/ Distribution Systems.

APPENDIX A

TABLE A.I. SAMPLE STUDY SYSTEM PARAMETERS.

Source		
Nominal voltage (L-L)		138 kV
Transformers		
	(T1)	**(T2)**
Rated power	5 MVA	5 MVA
Pri./Sec. voltage	138/25 kV	25/4.16 kV
Hybrid Loads		
Linear load		
Active power	850 kW	
Reactive power	526.78 kVAR	
Motorized load		
Nominal power	1 MVA	
Nominal voltage	4.16 kV	
Nonlinear load		
Nominal power	2 MVA	
α_0	10 degree	
α_1	30 degree	
ω_{01}	15 rad/s	
ω_{02}	25 rad/s	
C_d	825 uF	
R_0	16 ohms	
R_1	16 ohms	
Feeder		
Length	10 km	
Resistance	0.4 ohms/km	
Inductance	0.35 ohms/km	
DVSS		
Series Capacitor		
C_{S1}, C_{S2}	30 uF	
Filter		
Capacitance (C_f)	200 uF	
Inductance (L_f)	500 mH	
Resistance (R_f)	0.15 ohms	
Controller		
PI controller gains		
Proportional gain (K_P)		10
Integral gain (K_I)		1
Sliding Mode Controller (SMC)		
Slope of the sliding surface		1.5

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