Hierarchical Steady State Control of System wide Distributed Multi-FACTS Devices for Operational Enhancement Objectives

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Abstract*: Developed power systems in the world are well meshed with local, inter-regional and international connection making the increasing complex to operate. With advancement in power electronics, the control of these systems are faster with the aid of Flexible AC Transmission system devices (FACTs) introduced as control element in the system. As more of these devices are installed optimally in the transmission line at various locations, it is unarguable that it has the capabilities to control powerflows in major transmission line power corridors as well as improve voltage profiles of some critical buses within their respective operational domains of dominant influence. In addition, there tends to be a mutual conflict within the system. These unhealthy interactions within the system where these devices tend to operate beyond their operational domain. This paper is meant to x-ray and resolve these advance conflict as they occur in the system.*

I. Introduction

It is unarguable that optimally installed FACTSdevices possess flexible capabilities to control powerflows in major transmission line power corridors as well as improve voltage profiles of some critical buses within their respective operational domains of dominant influence. This is abstractly illustrated in Figure 1.0 as overlapping circular domains that encompass transmission lines and buses where mutual influences might occur. This has import on there maiming part of the grid including the line sand buses where other FACTS devices are placed. Basically, the control of the FACTS devices is local,i.e.no supervisory control that coordinates the actions of different devices. There is need therefore to incorporate higher level steady state coordinator to resolve and/or mitigate mutual influences among devices that could possibly result in adverse interactions in interconnected power systems. A two level supervisory steady state control based on optimal power flow has been developed as shown in Figure 1.0.The objective is to prevent conflicts among the devices by coordinating their actions to mitigate the danger of induced overloaded equipment and transmission line congestions. The optimal power flow solution yields voltage profile and active power losses for the system with embedded FACTS devices are Compared withthe base case scenario without FACTSdevices to establish, if any, voltage profile, technical losses and load ability improvements. Referring to Figure 1.0, each local controller dedicated to a FACT device that relies on local measurements such as line flows and bus voltage to adjust its parameter settings and transmit such information to central coordinator for further processing. The central coordinator acquires global system data to calculate sensitivity matrix to identify conflicts amongst FACTS devices and then implement OPF to determine their parameters to resolve such conflicts and insure optimum operational steady state performance at all times. Expectedly where conflicts do not exist, decentralized implementations of multi-FACTS devices are retained as optimal.
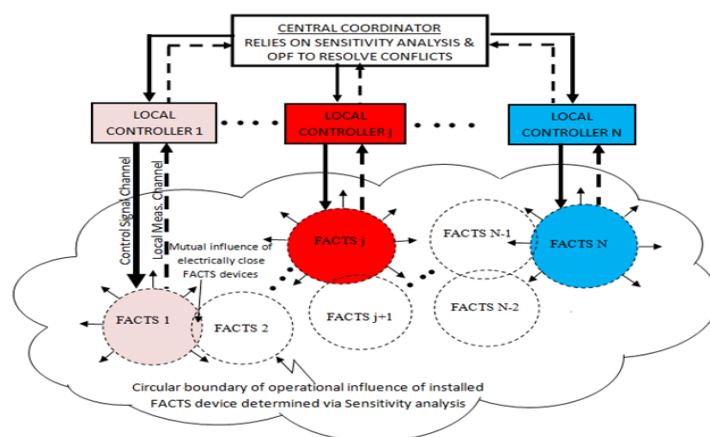
Figure 1.0: Interconnected Power System Equipped with Distributed N FACTS Devices under Hierarchical steady State Control Structure to Resolve Operational Conflicts

Table 1.0: Graph Theory Based Parameter Characterizations of the Two Test Systems

Graph Parameters	Nigerian Grid***	IEEE 30 bus**
Nodes/Buses	39	30
Elements (Transmission line + Transformers)	58	41
Diameter*	10	7
Number of Maximum Shortest Path	1	2
Average Node Degree	2.795	2.73
Clustering Coefficient	0.1457	0.2347
Average path length	2.123	3.47
Hub (Maximum number of connected lines)	Benin Bus	Node 6

*Maximum number of direct links between buses i and j within a given network;
****Extracted from reference [34];**
*** Computed via algorithmic procedure based on standard equations given in [69];

1.1 Description of Hierarchical Control Structure Implementation for Optimally Placed Multi-FACTS Devices in the Nigerian Grid System

The Nigerian grid system is described as structurally deficient because of its radial topology as further confirmed by its graph theory based characteristic features summarized in Table 1.2.   The inadequacy of transmission infrastructure has called for construction of new transmission power corridor to provide alternative route for power delivery to consumers in case of critical N-1 contingency or to carry diverted power from heavily loaded transmission lines during bilateral electricity transaction.   In order to make up for its inadequate transmission outlay, this research goal has pursued the optimal placements of FACTS devices in the Nigerian transmission system in order to secure the following steady state operational improvements:
1.   Minimization of network losses;
2.   Relief of transmission congestion during peak demand;
3.   Voltage stability enhancement; and
4.   Possible deferment of transmission reinforcement.

Figure 1.3 portrays the functional representation of the Nigerian national grid equipped with optimally designed multi-SVC and TCSC based on MILP solution of OPF formulation to realize the aforementioned operational improvements. The distributed SVCs and TCSC are then supervised by two-level hierarchical controller in keeping with the generalized hierarchical control structure of Figure 1.0. The functional task of the central coordinator is to resolve negative mutual interactions amongst installed FACTS devices if and when so identified on the basis of sound algorithmic framework that relies on periodic synchronous data information received from all local controllers. Note that each local controller is dedicated to specific FACTS device with demarcated zone of operational influence. The local controllers, in turn, rely wholly on local information of system quantities such as bus voltages, line flows and local network information to change optimal settings for their respective FACTS devices as system operating point changes. Central to the implementation of the proposed control structure are bi-directional communication and data acquisition channels configured around distributed phasor measurement units (PMUs) and wireless communication infrastructure []. At the local controller level, relying on data acquired periodically and the local neighbour network the optimal settings for each FACTS device are then determined using sensitivity analysis.
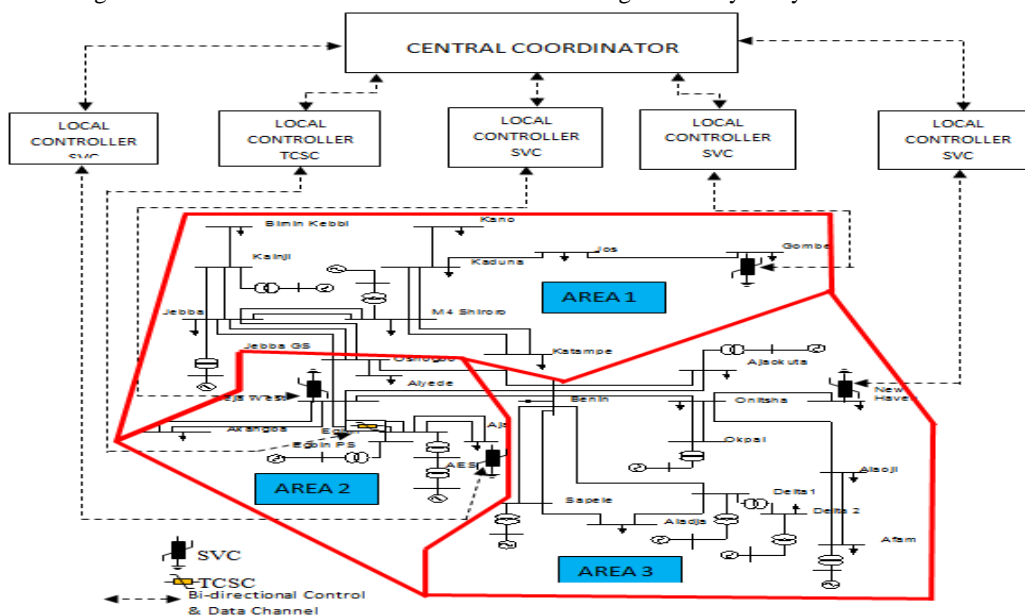
Figure 1.3: Functional Representation of Hierarchical Steady State Control of Optimal Placement of Multi-SVC and TCSC in Three- Area Nigerian Grid System

The central coordinator relies on the global data received and sensitivity computations to identify any existence of mutual interactions amongst electrically close FACTS devices. Upon detection of negative mutual interactions amongst FACTS devices will trigger implementation of OPF formulation to determine new optimal settings to override their locally computed settings. In the absence of mutual interactions amongst FACTS devices, their respective settings determined at local controller level are returned by the central coordinator as optimal for implementation. For the sake of completeness, the operating ranges of the various SVC and TCSC optimally sited in the Nigerian national grid and expected steady state operational improvements are presented in Table 5.2.

Table 5.3: Summary of

DESCRIPTION	FACTS Type	Bus Name	Line	Operating Limits of FACTS Devices	
				Minimum	Maximum
39- BUS NIGERIAN NATIONAL GRID FACTS DEVICE PLACEMENT	SVC1	Gombe	-	-20MVAr	50MVAr
	SVC2	Ikeja-West	-	-50MVAr	150MVAr
	SVC3	New-Haven	-	-10MVAr	50MVAr
	SVC4	Ajah	-	-10MVAr	75MVAr
	TCSC	-	Egbin HT-Ikeja West Line 5	$X_{TCSC_{min}} = -j0.1\Omega$	$X_{TCSC_{max}} = j0.1\Omega$
SYSTEM OPERATIONAL IMPROVEMENT SPECIFICATIONS	Network Loss Reduction for: • SVC1+SVC2 (2-Type) Installation; • SVC1+SVC2+SVC3 (3-Type) Installation; • SVC1+SVC2+SVC3+SVC4 (4-Type) Installation;			5.5% 7.4% 8.7%	13.75% 15.8% 16.8%
	Loadability Improvement Margin for: • SVC1+SVC2 (2-Type) Installation • SVC1+SVC2+SVC3+SVC4 (4-Type) Installation;			21% 24%	33% 38%
	Voltage Stability Margin Improvement for: • SVC1+SVC2 (2-Type) Installation • SVC1+SVC2+SVC3+SVC4 (4-Type) Installation;			12% 14%	16% 19%

Optimum number of FACTS required for minimum installation cost

We reiterate again that the Nigerian national grid admitted more of shunt FACTS type (SVC or STATCOM) and less of series FACTS type (TCSC) due to its radial topology. With the completion of on-going transmission reinforcements for more reliable and secure delivery of electricity to consumers, it is envisioned that more series or series-shunt FACTS types will be admitted. Fortunately, FACTS devices are re-locatable and expandable if and when their respective ratings and/or locations become suboptimal as consequence of rapid expansion of network infrastructure. Indeed, the expectation is that the Nigerian transmission infrastructure will witness rapid expansion driven primarily by opening of transmission entity to private participation but under unified operational management of regional independent system operators (ISOs)
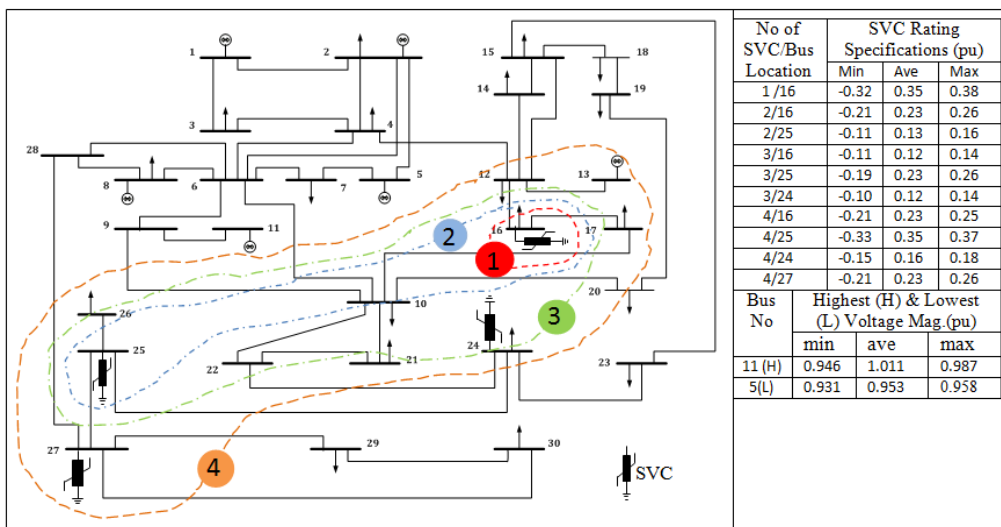1US$=N200

Figure 4.15: IEEE 30-Bus System Showing SVC Locations and Their Concatenated Grouping Installation Sequence

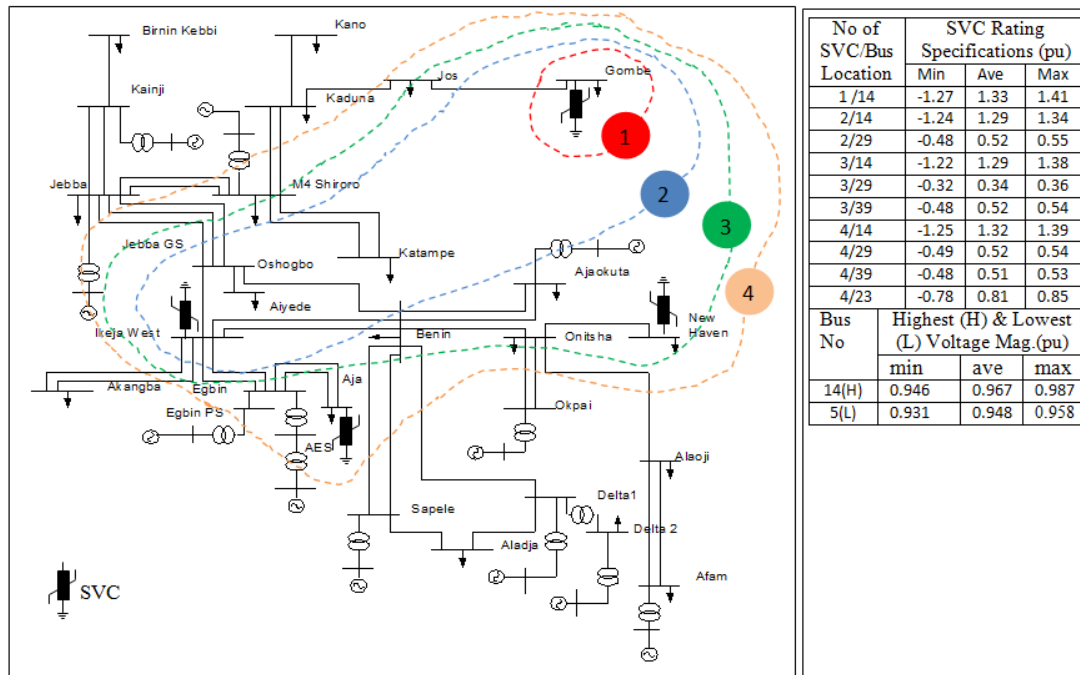| No of SVC/Bus Location	SVC Rating Specifications (pu)		
	Min	Ave	Max
1 /14	-1.27	1.33	1.41
2/14	-1.24	1.29	1.34
2/29	-0.48	0.52	0.55
3/14	-1.22	1.29	1.38
3/29	-0.32	0.34	0.36
3/39	-0.48	0.52	0.54
4/14	-1.25	1.32	1.39
4/29	-0.49	0.52	0.54
4/39	-0.48	0.51	0.53
4/23	-0.78	0.81	0.85
Bus No	Highest (H) & Lowest (L) Voltage Mag.(pu)		
	min	ave	max
14(H)	0.946	0.967	0.987
5(L)	0.931	0.948	0.958

Figure 4.18: 39-Bus Nigerian Grid System Showing SVC Locations and Their Concatenated Grouping Installation Sequences

II. Conclusion

Generalized hierarchical control architecture has been proposed to determine the steady state control setting of each distributed multi- FACTS devices in large interconnected network enabled by dedicated controllers at local level,   resolve all control conflicts and optimize parameter settings at supervisory level (Coordinator). This would engender efficient communication technologies and distributed phasor measurement units for data acquisition system. The design of a hierarchical control framework for the Nigerian grid and IEEE 30 Bus systems has been set forth as closure to this work.

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