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Use FACTS elements to improve energy exchange between countries in response to the high penetration of variable renewable energy

Usar los elementos FACTS para mejorar el intercambio energético entre países como respuesta a la alta penetración de energía renovable variable

BARESKH-ONJI, Aboud†*

Istitulto Politécnico Nacional, Escuela Superior de Comercio y Administración Sto.Tomás, Ciudad de México, México.

ID 1[er] Autor: *Aboud, Barsekh-Onji* / **ORC ID:** 0009-0004-5440-8092, **CVU CONAHCYT ID:** 944116

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Abstract

Integrating Variable Renewable Energy sources (VRE) into Electric Power System (EPS) requires optimizing the synergy between VRE characteristics, PES flexibility elements, and local Electric Market operations. However, during advanced integration phases, where VRE accounts for a significant portion of the system's energy, and in the face of stability issues caused by energy excess, cross-border energy exchange appears to be one of the most effective solutions for Energy Management. In this investigation, to highlight the role of Flexible Alternative Current Transmission Systems (FACTS) elements to ensure the required flexibility in these energy exchange operations, a modeling strategy Methodology was implemented in MATLAB and SIMULINK to design a Static Var Compensator (SVC) and simulate its connection to a high-voltage power line between Turkey and Syria, observing its response these changes in load flow. This investigation contributes to the VRE integration strategy, identifying FACTS elements as a solution to manage excess energy and achieve efficient energy exchange.

Integration, Flexibility, Renewable energy resources

Resumen

La integración de las fuentes de Energía Renovable Variable (ERV) a los Sistemas Eléctricos de Potencia (SEP) requiere optimizar la interacción entre las propiedades de estas fuentes, los factores de flexibilidad del SEP y la operación del Mercado Eléctrico local. Sin embargo, para las fases avanzadas de integración donde la ERV forma gran parte de la energía en el sistema, y ante los problemas de estabilidad causados por excedentes de energía, el intercambio energético entre los países es una de las mejores soluciones para administrar la energía en tiempo real. En esta investigación, y para destacar el rol de los elementos FACTS (Sistemas Flexibles de Transmisión de Corriente Alterna) en garantizar la flexibilidad requerida al realizar estas operaciones de intercambio energético, se ejecutó una estrategia metodológica de modelaje en MATLAB y SIMULINK para diseñar un compensador estático de energía reactiva (SVC), y simular su conexión a una línea de alta tensión entre Turquía y Siria con la finalidad de observar su respuesta ante los cambios de flujo de energía. Esta investigación contribuye a las estrategias de integración de ERV, identificando a los elementos FACTS como una solución en la administración de los excesos de energía, logrando un eficiente intercambio energético.

Integración, Flexibilidad, Fuentes de energía renovable

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* Author's Correspondence (E-mail: abarsekho2300@alumno.ipn.mx)
† Researcher contributing as first author.

Introduction

The integration of Variable Renewable Energy sources (VRE) into Electric Power Systems (EPS) has been an important research topic in recent years, aiming to integrate new technologies, specifically photovoltaic panels, and wind generators, into existing power systems. This effort also seeks to expand opportunities for extensive private sector participation in the electricity market. However, the integration strategy includes all the technical, administrative, financial, and market design changes required to enable the substantial incorporation of VRE, safely and profitably, into a country's PES.

The physical nature of electricity and the principles of electric power system stability require real-time balancing between generation and demand, underscoring the importance of adhering to the technical and operational constraints of the EPS.

In addition, it should be noted that the ease or difficulty of VRE integration into EPS depends on other factors. It is easier to integrate VRE into systems where energy demand and VRE production are positively correlated, both in normal day-to-day patterns, and where power system flexibility is crucial to facilitate VRE adoption (International Energy Agency, 2022).

In fact, to establish a strategic model for the integration of VRE, specific characteristics of the EPS assume a pivotal role in addressing this challenge. These characteristics are summarized in Table 1.

General structure and technical factors	- Geographic location of VRE sources and their main characteristics. - The demand forecast. - The correlation between demand and reproducible energy from ERV sources - The flexibility of the plants that make up the electric power system. - Interconnection, storage capacity and demand response.
Operation system, market design and regulation	- Operational decisions, and their proximity to real-time execution, for the plants that make up the electric power system and its interconnection. - The type of market design according to demand, whether long or short term. - The Network Code and the current regulation regarding the issue of VRE sources.
Fundamentals of production and demand	- The evolution of energy demand, where the growth in demand could be a reason to demand an urgent integration model for VRE sources.

Table 1 Principal characteristics of Electric Power System
Source: Own elaboration

Consequently, based on the data and experiences of several countries regarding the challenge of integrating Variable Renewable Energy (VRE), the International Energy Agency (IEA) has defined distinct phases towards achieving full integration of these sources. These phases (Table 2) were established based on the percentage of VRE penetration compared to the percentage of energy produced by the EPS in accordance with demand. (International Energy Agency, 2018).

Phase 1	The VRE sources do not have an impact on the EPS.
Phase 2	The VRE sources have a minor to moderate impact on the EPS
Phase 3	The VRE sources dictate the operational pattern of the EPS
Phase 4	The VRE sources generate most of the energy circulating in the EPS
Phase 5	The VRE sources produce surplus amounts of energy for days to weeks
Phase 6	The VRE sources produce surplus amounts of energy seasonally

Table 2 Phases off integration of VRE into EPS
Source: Own elaboration based on IEA

For years, research in the technical aspects of an integration model has focused on various areas of interest, beginning with diverse models for demand forecasting, including econometric models, regression models, or neural networks (Sambaiah & Jayabarathi, 2019), on the other hand, some researchers detailed the planning of energy storage systems to integrate high proportions of VRE (Auguarda et al., 2023).

Also, several studies can be found addressing the optimization of the location and size of VRE (Gözel & Hocaoglu, 2009) and (Ghosh et al., 2010), while other investigators have sought to optimize the aforementioned factors based on the reduction of energy losses (Gil-González et al., 2021).

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Moreover, the authors of (Wang & Nehrir, 2004) employed analytical expressions based on active and reactive loads to reduce energy losses and optimize the location of VRE sources.

Similarly, the reconfiguration of electric networks has been an extensively researched topic, aimed at modifying the operating conditions of the EPS to accommodate VRE sources in a Distributed Generation (DG) system (Koutsoukis et al., 2017).

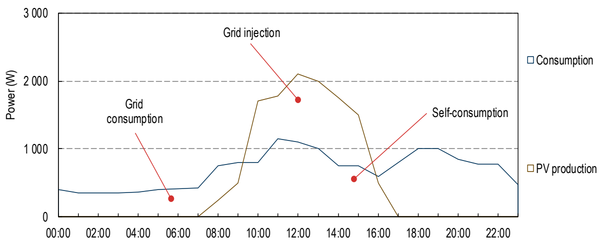

Figure 1 Excess solar PV production compared to demand
Source: IEA, 2018

Another critical point is that the production of VRE has different levels of uncertainty at different times and at different ranks within the EPS. This implies that as VRE gains a larger share in the electrical system and converts pertinent for decision-making regarding its disposition (Figure 1), whether through reserves or energy exchange.

Such as one of the most prominent examples of using interconnection to achieve efficient energy exchange during surplus hours from VRE sources was the interconnection project among the Southeast Asian countries (ASEAN) (International Energy Agency, 2019)

In response to various EPS stability challenges, the utilization of Flexible Alternative Current Transmission Systems (FACTS) has emerged. These FACTS systems, based on power electronics (Schulze et al., n.d.), enhance the controllability and stability of the electrical system, increasing its capacity to transmit energy by flexibly modulating the injected or absorbed reactive power at a specific network node (International Energy Agency, 2021).

Due to the distinctive behavior of high-voltage lines concerning voltage stability (Oliveira Da et al., n.d.) achieving control over their operation during energy exchange require a high level of real-time flexibility to ensure the stability of the Power Electric System.

Above all, this research adds significant value to the integration strategies of Variable Renewable Energy sources into EPS, highlighting the role of FACTS elements in reconfiguring the electrical grid in response to changes generated by surplus electrical energy from VRE sources, including the control of energy exchange lines between countries.

In the case of electrical systems with a high penetration percentage of VRE, the injection of excess energy can lead to voltage increases at certain nodes and result in an excess of energy that must be managed to avoid affecting the stability factors of the electrical grid.

The hypothesis of this investigation is the improvement of the stability of an interconnected Electric Power System when faced with a high level of penetration of VRE sources.

The main objective of the research is to emphasize the effect of FACTS elements in improving the flexibility of an interconnected electrical network with high ERV penetration.

The specific objectives of the research are:

- Determine the optimal locations and quantities of SVCs in the Syrian electrical grid to address excess VRE penetration, considering an energy exchange line with Turkey.

- Design a Static Var Compensator (SVC) and construct a simulation of its connection to a high-voltage line between Turkey and Syria to observe its response to changes in energy flow.

Methodology to be developed

In this paper, a program design based on the Newton-Raphson method was developed for the calculation of nonlinear differential equations representing a PES (Eltamaly et al., 2018). Additionally, the optimal placement of compensators was determined using the mathematical sensitivity theory method (Contreras Aguilar, 2005).

The Power Electric System operation is described by the following equations:

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$$P_k = |V_k|.\sum_{j=1\ \&\ j\neq k}^{j=n} |Y_{kj}|.|V_j|.\cos(-\theta_{kj} - \delta_j + \delta_k) + |V_k|^2.|Y_{kk}|.\cos(\theta_{kk}) \quad (1)$$

$$Q_k = |V_k|.\sum_{j=1\ \&\ j\neq k}^{j=n} |Y_{kj}|.|V_j|.\text{sen}(-\theta_{kj} - \delta_j + \delta_k) - |V_k|^2.|Y_{kk}|.\text{sen}(\theta_{kk}) \quad (2)$$

Where: P_k is the stability equation for the active power at the node (k), Q_k is the stability equation for the reactive power at the node (k), V_j, δ_j is the length and angle of voltage at node (j), Y_{kj} , θ_{kj} is the length and angle of the admittance of the line between nodes (k) and (j). In this case, two conditions were established for the execution of the Newton-Raphson method:

- Voltage condition:

$$|V_i| = |V_i|_{spec} \quad (3)$$

Where: $|V_i|_{spec}$ is the length of voltage that a node, with reactive power controller, can achieve within its allowed limits.

- Reactive energy condition:

$$Q_i^{min} \leq Q_i \leq Q_i^{max} \quad (4)$$

Where: Q_i is the reactive energy generated in the control node, with its minimum limits (Q_i^{min}) and maximum limits (Q_i^{max}).

The method (Figure 2) was applied to the 230KV electrical grid of the Republic of Syria, consisting of 51 nodes (Alwazah et al., n.d.; Hamzeh, 2004), under the following two scenarios:

- First: without applying any reactive power compensation and considering the massive generation of renewable energy.

- Second: with the application of three points of compensation using SVC at three locations closer to the interconnection lines with Turkey. The results are presented in Graphic (1)

The system allocates the quantities in table 3 of reactive power to be generated at the three nodes.

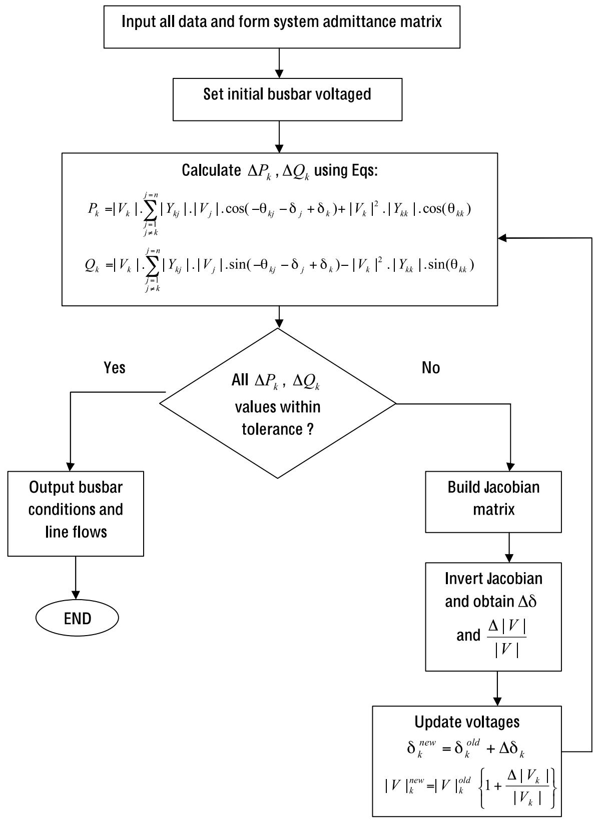
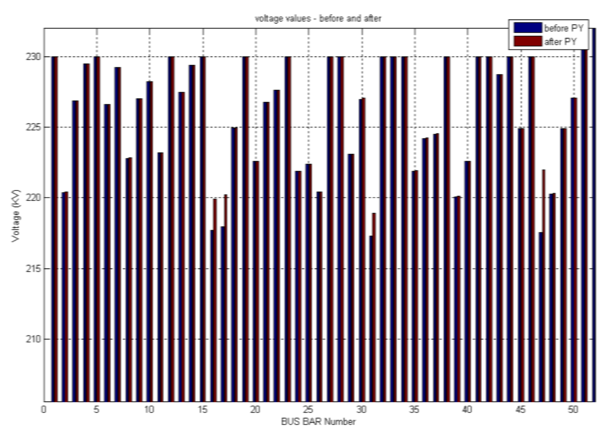


Figure 2 Newton-Raphson method applied in this investigation
Source: (Eltamaly et al., 2018)



Graphic 1 Node voltages before and after compensating for reactive power in the nodes of the Syrian 230KV power grid.
Source: Own elaboration based on results of the applied method

PY number	Node number	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)
1	16	40	-100	200
2	47	20	-100	200
3	48	160	-100	200

Table 3 Reactive power results
Source: Own elaboration based on results of the applied method

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Based on the initial results, the design of the Static Var Compensator (SVC) with voltage controller, as depicted in Figure 3, and the equivalent circuit is shown in Figure 4 was undertaken, following the subsequent equations:

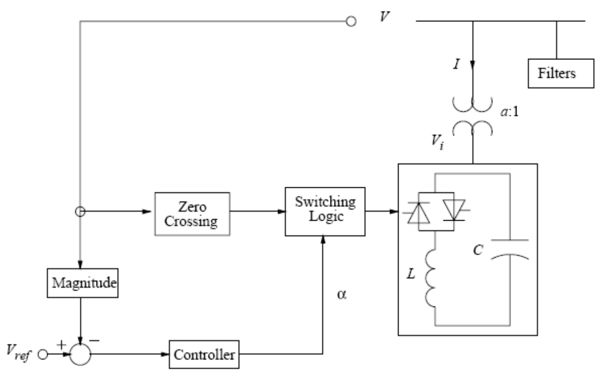


Figure 3 SVC with voltage controller
Source: (Schulze et al., n.d.)

Calculation of thyristor firing angles:

$$B_{SVC}(\alpha) = B_{TSC}(\alpha) - B_{TCR}(\alpha)\frac{X_L - \frac{X_c}{\pi}(sen(2\alpha) - (2\pi - 2\alpha))}{X_c X_L} \quad (5)$$

Where:

$$X_{TCR}(\alpha) = \frac{\pi X_L}{sen(2\alpha) + (2\pi - 2\alpha)} \quad (6)$$

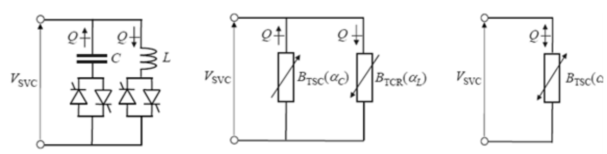


Figure 4 Equivalent Circuit of SVC with voltage controller
Source: (Schulze et al., n.d.)

Therefore, the reactive power generated by the SVC as a function of angle (α) is given in equation (7).

$$Q_{SVC}(\alpha) = -U_k^2 B_{SVC}(\alpha) = -U_k^2 \frac{X_L - \frac{X_c}{\pi}(sen(2\alpha) - (2\pi - 2\alpha))}{X_c X_L} \quad (7)$$

Thus, the SVC was designed with the following reactive power values in accordance with the network requirements, considering that it will be supplied by a 300MVA, 230/66KV transformer with a reactance (XT) of 15% and a maximum voltage drop of 0.01 per unit (p.u.) for every 100VA.

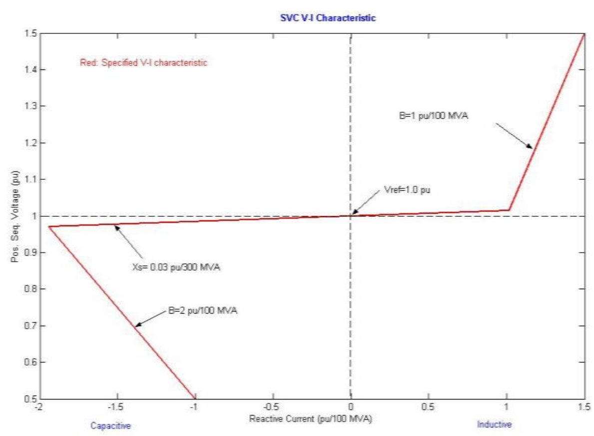
$$Q_{TSC} = 3 \times 94\ Mvar \quad (8)$$

$$Q_{TCR} = 109\ Mvar \quad (9)$$

The SVC elements calculation was supported out for the nominal voltage (230KV), maximum voltage (232.3KV), and minimum voltage (223.1KV), resulting in the technical specifications of the designed SVC (Table 4). The technical data sheet is shown in Table 5 and its V-I Characteristic in Graphic 2.

$X_{L-rated}$	$X_{Transformer}$	X_{L-TCR}
39.96 Ω	2.178 Ω	37.78 Ω
L_{TCR}	$X_{C-rated}$	C
0.36 Henri	15.44 Ω	20.606mF

Table 4 Technical specifications of the designed SVC
Source: Own elaboration based on results of the applied method

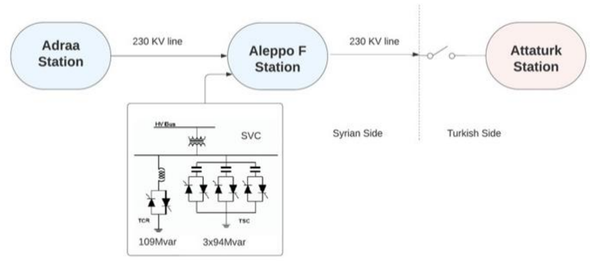


Graphic 2 SVC V-I Characteristics
Source: SVC Model output

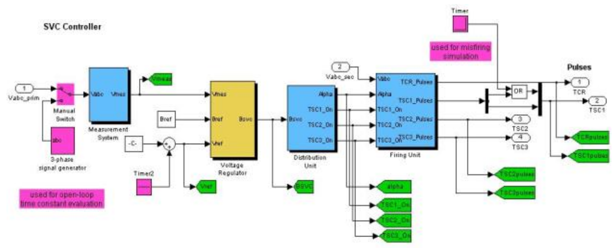
Application	230KV
Voltage Level	10KV
Type	SVC (TCR/3 & TSC)
TCR capacity	109Mvar
TSC capacity	3 x 94Mvar
Valves structure	Open
Cooling Method	Fully closed pure water cooling
Control System	Full digital
Response Time	9 msec max
Regulation range	-100% to +100%

Table 5 SVC Data sheets
Source: Own elaboration based on results of the applied method

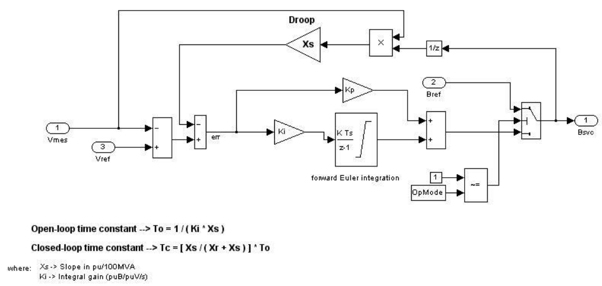
Based on the design results, a model was prepared in MATLAB SIMULINK 2022 for the installation of the SVC at the 'Aleppo F' station, where the 230KV interconnection line with Turkey originates (Graphic 3). The SVC control blocks are seen in Graphic 4, and the voltage controller in Graphic 5, with the pulse outputs assigned to each of the compensator elements. The model examined voltage variations in various scenarios at three key nodes: Aleppo F, Adraa, and Atatruck.



Graphic 3 Model connection diagram
Source: Own elaboration



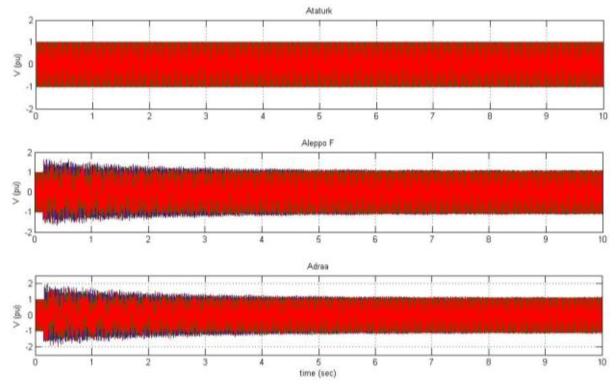
Graphic 4 SVC Controller
Source: Own elaboration on MATLAB-SIMULINK



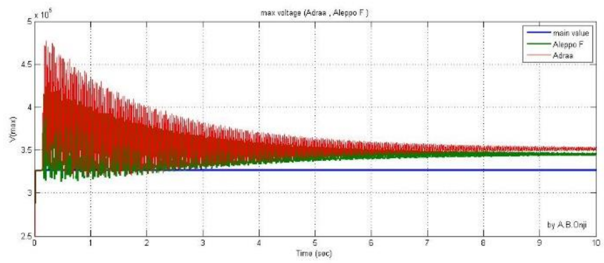
Graphic 5 SVC Voltage regulator.
Source: Own elaboration on MATLAB-SIMULINK

Results

Initially, the model of the electrical grid without activating the SVC and under normal operation was applied. To study the improvement afforded by the SVC, a drastic scenario was analyzed in which, at time 0.15 of the simulation, the line on the 'Atatürk' node side was opened, causing a voltage increase (Graphic 6) at the Aleppo F node (1.65 per unit) and the Adraa node (1.71 per unit). Furthermore, high voltage values applied to the isolating elements in both nodes were detected in this case compared to the main value (Graphic 7).

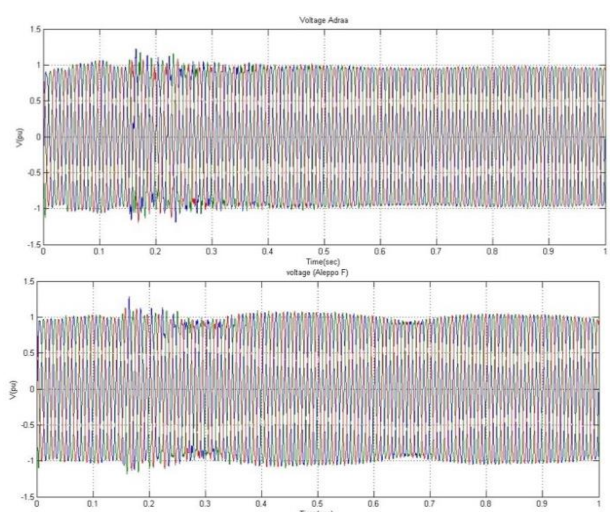


Graphic 6 Voltage variation in nodes: “Aleppo F”, “Adraa” and “Ataturk”, without SVC
Source: SVC Model output



Graphic 7 High voltage values applied to the isolating elements in both nodes compared to the main value
Source: SVC Model output

In the second simulation, the SVC installed at the 'Aleppo F' node is activated, and the same procedure as before is repeated. Up on observing the results, it can be appreciated that the SVC control system operated correctly through absorbing the reactive power generated by the open line (Graphic 8), thus maintaining voltage stability at the nodes very close to nominal values. Additionally, Graphic 9 depicts the response of the currents from the TSC and TCR in comparison to the applied voltage variation.



Graphic 8 Voltage variation in nodes: “Aleppo F”, “Adraa” and “Ataturk”, with SVC
Source: SVC Model output

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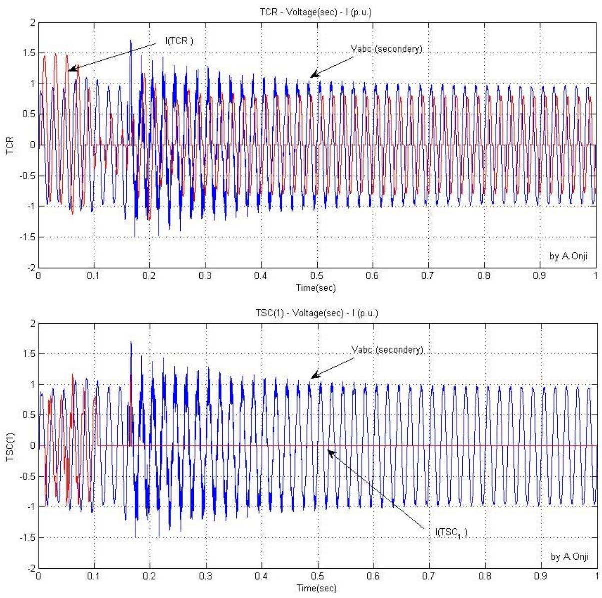

Graphic 9 High voltage values applied to the isolating elements in both nodes compared to the main value.
Source: SVC Model output

The above results demonstrate the rapid response of FACTS elements to momentary changes in energy injected at nodes in an Electric Power System by VRE sources, even in addressing specific scenarios such as the operation in open-circuit conditions for a high-voltage line.

Financing

This work has been funded by the author.

Annexes

I. 230KV grid nodes Data

Node	Un	Q_load	P_load	Q_gen.	P_gen.	Θ	V
1	230	0	0	0	0	0	230
2	230	101.4405	169.0674	0	0	0	0
3	230	67.62698	200	0	0	0	0
4	230	67.91847	113.1975	0	0	0	0
5	230	0	0	0	0	0	230
6	230	51.303	85.505	0	0	0	0
7	230	29.149	48.582	0	0	0	0
8	230	96.19355	160.3226	0	0	0	0
9	230	90.94663	151.5777	0	0	0	0
10	230	68.209	113.683	0	0	0	0
11	230	69.667	116.1124	0	0	0	0
12	230	20.75944	34.59	408.54	660	0	230
13	230	0	0	0	0	0	0
14	230	37.31144	62.18573	0	0	0	0
15	230	23.028	38.38	92.85	150	0	230
16	230	85.11672	141.8623	0	0	0	0
17	230	0	0	0	0	0	0
18	230	100.2745	167.1241	0	0	0	0
19	230	53.63519	89.39198	439.49	710	0	230
20	230	72.29091	120.4848	0	0	0	0
21	230	102.0235	170.0391	0	0	0	0
22	230	102.315	170.5249	0	0	0	0
23	230	0	0	46.425	75	0	230
24	230	103.1894	171.9824	0	0	0	0
25	230	121.2622	202.1036	0	0	0	0
26	230	110.7683	184.6139	0	0	0	0
27	230	50.13724	83.56207	371.4	600	0	230
28	230	24.48563	40.80938	55.71	90	0	230
29	230	53.63519	89.39198	0	0	0	0
30	230	94.44457	157.4076	0	0	0	0
31	230	64.12903	106.8817	0	0	0	0
32	230	34.97947	58.29912	185.7	300	0	230
33	230	46.6393	77.73216	371.4	600	0	230
34	230	51.30323	85.50538	278.55	450	0	230
35	230	82.201	137.0029	0	0	0	0
36	230	97.65	162.75	0	0	0	0
37	230	93.86	156.43	0	0	0	0
38	230	0	0	0	0	0	230
39	230	116.5982	194.3304	0	0	0	0
40	230	53.0522	88.42033	0	0	0	0
41	230	23.90264	39.83773	408.54	660	0	230
42	230	26.8176	44.69599	389.97	630	0	230
43	230	50.42874	84.0479	0	0	0	0
44	230	0	0	309.5	500	0	230
45	230	102.315	170.52	0	0	0	0
46	230	0	0	0	0	0	0
47	230	72.29091	120.4848	0	0	0	0
48	230	71.999	119.999	0	0	0	0
49	230	85.11672	141.8612	0	0	0	0
50	230	85.11672	142.8328	0	0	0	0
51	230	0	0	0	0	0	0

Table 6 230KV Syrian gird nodes data
Source: (Alwazah et al., n.d.; Hamzeh, 2004)

II. 230KV grid lines Data

Line	KT	B	G	X	R	to	from
1	1	7.7	0	0.43	0.1	2	39
2	1	396.5	0	43.84	10.95	3	2
3	1	39.7	0	4.39	1.07	8	2
4	1	80.5	0	8.88	2.18	21	2
5	1	28.8	0	3.18	0.76	48	2
6	1	225.79	0	24.96	6.125	9	3
7	1	60.48	0	6.68	1.64	22	3
8	1	55.008	0	6.08	1.49	41	3
9	1	535.39	0	59.19	14.52	5	4
10	1	51.84	0	5.76	1.4	12	4
11	1	61.945	0	6.84	1.667	22	4
12	1	560.16	0	61.92	15.2	5	4
13	1	125.4	0	13.865	2	19	4
14	1	14.62	0	1.615	0.396	41	4
15	1	388.8	0	42.98	10.54	1	4
16	1	443.52	0	49	12	6	5
17	1	247.104	0	27.32	6.7	7	5
18	1	49.598	0	5.481	1.348	10	5
19	1	63.36	0	7	1.72	23	5
20	1	48.096	0	5.31	1.3	14	6
21	1	158.4	0	17.51	4.3	1	6
22	1	28.224	0	3.18	0.76	49	6
23	1	278.496	0	30.78	7.55	14	7
24	1	59.974	0	6.629	1.622	42	7
25	1	99.36	0	10.98	2.7	21	8
26	1	22.752	0	2.515	0.615	30	8
27	1	184.32	0	20.37	5	13	9
28	1	71.136	0	5.81	1.425	19	9
29	1	482.688	0	53.36	13.1	11	10
30	1	411.84	0	45.53	11.17	18	10
31	1	39.6	0	10.34	2.54	23	10
32	1	391.68	0	43.3	10.6	15	11
33	1	374.4	0	41.39	10.15	18	11
34	1	224.64	0	24.83	6.1	29	11
35	1	20.968	0	2.316	0.566	1	14
36	1	149.76	0	16.55	4.1	51	54
37	1	250.56	0	27.7	3.46	29	15

38	1	15.2	0	12.73	3.12	46	15
39	1	155.52	0	17.19	4.2	17	16
40	1	138.24	0	15.28	3.75	31	16
41	1	161.28	0	17.83	4.37	30	16
42	1	89.28	0	9.87	2.42	28	18
43	1	37.152	0	4.105	1.01	43	19
44	1	142.272	0	15.72	3.86	20	19
45	1	11.52	0	1.273	0.312	40	20
46	1	42.192	0	4.665	1.145	27	21
47	1	86.4	0	9.55	2.34	57	58
48	1	305.28	0	33.75	8.28	53	58
49	1	46.08	0	5.09	1.25	33	22
50	1	144	0	15.92	3.9	25	24
51	1	118.368	0	13.08	3.21	34	24
52	1	45.504	0	5.06	1.23	26	25
53	1	28.224	0	3.18	0.76	49	25
54	1	169.92	0	18.79	4.61	42	25
55	1	288	0	31.84	7.8	42	26
56	1	66.24	0	7.32	1.8	30	27
57	1	72	0	7.96	1.95	45	27
58	1	322.56	0	35.66	8.75	31	27
59	1	247.68	0	27.38	6.72	47	28
60	1	48.96	0	5.41	1.33	8	30
61	1	55.296	0	6.11	1.5	36	30
62	1	14.112	0	1.59	0.38	44	30
63	1	161.28	0	17.83	4.37	35	32
64	1	217.44	0	24.03	5.9	40	34
65	1	34.56	0	3.82	0.94	48	35
66	1	48.96	0	5.41	1.33	37	35
67	1	17.537	0	1.942	0.478	37	36
68	1	57.6	0	31.84	7.8	28	38
69	1	50.4	0	5.57	1.365	50	1
70	1	59.04	0	6.525	1.6	49	1
71	0.575	0	0	1.4	0.2	28	52
72	0.575	0	0	1.4	0.2	14	54
73	0.575	0	0	1.4	0.2	33	53
74	0.575	0	0	1.4	0.2	4	56
75	0.575	0	0	1.4	0.2	34	55
76	0.575	0	0	1.4	0.2	32	57
77	0.575	0	0	1.4	0.2	21	58
78	0.575	0	0	1.4	0.2	37	59
79	0.575	0	0	1.4	0.2	44	60
80	1	520	0	59.6	11.2	53	52
81	1	220	0	23.11	4.18	53	56
82	1	506	0	52.78	9.56	54	56
83	1	305.28	0	33.75	8.28	55	56
84	1	220	0	23.11	4.18	54	55
85	1	475	0	49.45	8.97	59	53
86	1	220	0	23.11	4.18	60	59
87	1	305.28	0	33.75	8.28	60	58
88	1	161.28	0	17.8	4.37	61	52
89	1	220	0	23.1	4.18	62	60
90	1	305.3	0	33.7	8.28	63	59
91	1	220	0	23.11	4.18	64	55
92	0.575	0	0	1.4	0.2	64	34

Table 7 230KV Syrian gird lines data,
Source: (Alwazah et al., n.d.; Hamzeh, 2004)

Conclusion

It is increasingly recognized that integrating renewable energy into energy systems is one of the most important challenges for the energy future of countries. Considering the high prevalence of variable renewables energy in the electricity grid, energy exchange between countries and regions is one of the most effective measures. This study specifically examines the response of SVC as one of the FACTS elements to changes in network power flows to ensure voltage stability of interstate interconnection lines as a control measure for VRE overshoot. This ensures that these FACTS elements can instantly reconfigure the grid in response to any changes. However, it should be noted that the correct operation of FACTS components depends not only on their correct design, but also on their location in the network and their characteristics. It is recommended to consider the wide possibilities of FACTS elements when reconfiguring grids in countries where VRE penetration is currently low, such as Mexico.

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