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The Impact of Superconducting Cables in Power Transmission Systems- a Case Study in Turkey

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Abstract

Power systems encounter multiple problems during planning, operating and analyzing processes. Superconducting technologies can be the solution for some of these problems. In this study usage of superconducting cables in the Turkey transmission system are simulated to see the affects. One base and two different cases are discussed. Power flow analysis and voltage stability analysis are done for the real Turkish 22 bus system. The voltage stability is analyzed by using the loading factor. The results show the decrease in losses and the increase of the system's capacity. The amount of CO_2 emission is also presented. This study is a rough analyze but a precursor for further studies which will also contain an economical analyze considering the cooling costs and new topology of system.

Keywords: Superconducting filaments and wires, Load flow, Power system stability.

1. INTRODUCTION

Over the years, electricity has become a fundamental requirement in all areas of life. This required electricity is generated by generators, transformed by transformers into appropriate voltage values, transported over long distance transmission lines, transformed back into appropriate voltage and current for local distribution [1]. The involvement of electric energy in all areas of life enhances the importance of planning and analysis of power systems. However, power systems are constantly faced with many problems such as short circuit, overload, voltage sagging, insufficient space for new transmission lines and high power losses. In the World Bank data Turkey's power network, transmission and distribution losses between 2006 and 2010 totaled 14%, while this value increased by 15% of generation between 2011 and 2015. Loss should be minimized in traditional transmission and distribution systems (between 3% and 6%). In addition to losses, it is anticipated by that by 2030, the world's energy needs will increase by more than 20%. This energy requirement is not only due to population growth, but also because new technologies enter into life (electric vehicles and new technologies). The increase in energy demand will lead to more power transmission in urban areas, high loss and voltage drop problems [1]. These problems will lead to increased intention and usage of new concepts such as Smart Grid's, DG (Distributed Generation), power control, capacity placement

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and tap changer transformers. However, the use of these systems will cause problems related to voltage and frequency stability, power control and voltage regulation. Moreover, the use of these systems also increases the cost of the power system [1].

Each component in the power system can be replaced with a similar device made from superconducting materials with better properties. Many applications have been made and continues to be developed from superconducting materials in order to make the power system more stable, reliable and efficient. Also when replaced with superconductor components the size/weight of the system and the problems the system faces (voltage sag, overload etc.) reduces. The most important of these applications are Superconducting Magnetic Energy Storage (SMES) [2-6], power transmission cables [7-10], power transformers and Fault Current Limiter's (FCL) [11-14]. In Fig. 1 the problems in the future that are waiting the power systems are shown. Due to these problems there will be tasks for power engineers [1]. By using superconducting materials in power systems, most of the requirements can be met, such as energy efficiency, minimizing losses, flexibility in production and storage, a harmless (reducing CO_2 emission) and a more reliable network.

In this study, we concentrate on superconducting cables because of their low impedances to show the effect in the power systems. The load flow and loading factors are analyzed. The role of superconducting cables on loading factor is shown. Besides the advantages there are some disadvantages like cooling the cable in all times and cost of the system. In special critical situations superconductor applications have been used in the world. In this point of view we have made a simulation model for the Turkey 380 kV transmission system to observe the loss and voltage behaviors when superconductor cables are used in different cases.

2. TEST SYSTEM

In order to analyze the impact of superconducting cables on power transmission systems, the Turkish 22 Bus 380 kV transmission system is used in the simulations. A single line diagram of this network is shown in Fig. 2. The Turkish 22 Bus 380 kV transmission system consists of 22 buses interconnected by means of 26 3-phase overhead lines and 10 loads on the buses. The total active and reactive power demands of the system are 3466 kW and 2102 kVAr, respectively. The system data is taken from [15]. The generator voltage magnitudes at PV buses, line parameters (in pu) and load values (in pu) at load buses are given at Table I and Table II. The buses in Turkish 22 Bus 380 kV transmission system were numbered, shown in Table I, in simulations to facilitate the results.

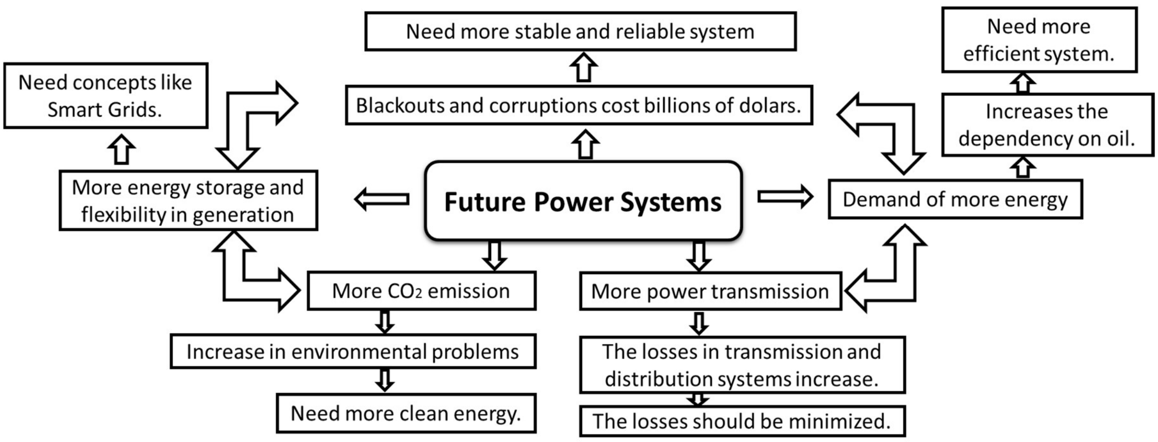


Figure 1 Problems waiting the power systems in future and the resulting tasks

Table 1

Properties of 22 Bus System [15]

Bus Number	Bus Type	Bus Voltage (pu)	Bus Angle	Load		Generation	
				P (MW)	**Q (MVAr)**	**P (MW)**	**Q (MVAr)**
1	Slack bus	1.015	0	0	0	0	0
2	PQ (load)	1	0	0	0	0	0
3	PQ (load)	1	0	236	146.25	0	0
4	PQ (load)	1	0	433	268.34	0	0
5	PQ (load)	1	0	236	146.259	0	0
6	PQ (load)	1	0	0	0	0	0
7	PQ (load)	1	0	172.8	107.2	0	0
8	PQ (load)	1	0	264.63	163.6	0	0
9	PQ (load)	1	0	304	188.4	0	0
10	PQ (load)	1	0	141	87.38	0	0
11	PQ (load)	1	0	205	127.04	0	0
12	PQ (load)	1	0	277.2	171.66	0	0
13	PQ (load)	1	0	248.7	153.69	0	0
14	PQ (load)	1	0	292	180.96	0	0
15	PQ (load)	1	0	229	141.92	0	0
16	PV (generation)	1.015	0	0	0	680	0
17	PV (generation)	1.0172	0	0	0	601	0
18	PV (generation)	1.0111	0	204	126.4	430	0
19	PV (generation)	1.017	0	178.1	110.3	530	0
20	PV (generation)	1.012	0	215.9	133	390	0
21	PV (generation)	1.012	0	18	11.15	520	0
22	PV (generation)	1.0251	0	344.7	213.2	490	0

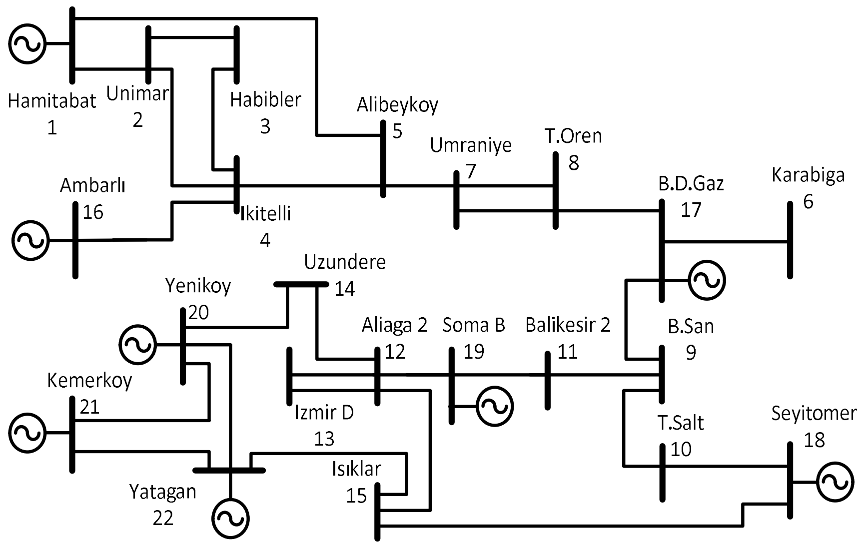


Figure 2 The Turkish 22 Bus 380kV transmission system

Table 2

Parameters of lines [15]

Bus to Bus	R (pu)	X (pu)	B/2 (pu)	Bus to Bus	R (pu)	X (pu)	B/2 (pu)
1-2	0.002165	0.020001	0.222098	**11-19**	0.001564	0.014450	0.1604605
1-5	0.002444	0.028082	0.4612905	**12-19**	0.001979	0.018287	0.203061
2-4	0.002080	0.019221	0.213437	**12-13**	0.000019	0.000288	0.0049555
4-16	0.000528	0.004860	0.1752395	**12-14**	0.001108	0.012733	0.2091535
4-5	0.000351	0.004182	0.0639695	**12-15**	0.001145	0.010580	0.1174845
5-7	0.000620	0.007384	0.1129485	**15-22**	0.002357	0.027081	0.444846
7-8	0.000769	0.007119	0.078705	**15-18**	0.006840	0.063202	0.7018005
8-17	0.004125	0.038120	0.4322905	**14-20**	0.002591	0.029764	0.3619415
6-17	0.002790	0.033208	0.507974	**20-22**	0.001007	0.009266	0.1059455
9-17	0.000389	0.003592	0.0398905	**21-22**	0.001143	0.010518	0.120261
9-10	0.002112	0.019471	0.2216565	**20-21**	0.000309	0.002839	0.0324665
9-11	0.002630	0.024305	0.2698815	**3-4**	0.000417	0.004962	0.075904
10-18	0.001010	0.009314	0.1060295	**2-3**	0.001364	0.016234	0.2483265

3. CASE STUDIES AND SUPERCONDUCTING CABLE PARAMETERS

Three case studies have been carried out through the 22-bus Turkish transmission system as follows.

• First case (base case), this is the base case which define the power flow results of Turkish 22 Bus 380kV transmission system obtained by PSAT in MATLAB.

• In the second case, the effect of superconductor cable is investigated by replacing the line (line between bus 14 and 12) connected to the critical bus with a superconducting cable.

• In the third case, in order to see the impact of superconducting cables in the overall system, all lines are replaced by superconducting cables.

The cable that was used in the simulation model is shown in Figure 3. The cable has 3 phases in one and cryostat channels for cooling [16]. The cable can carry up to 9000 Amp's.

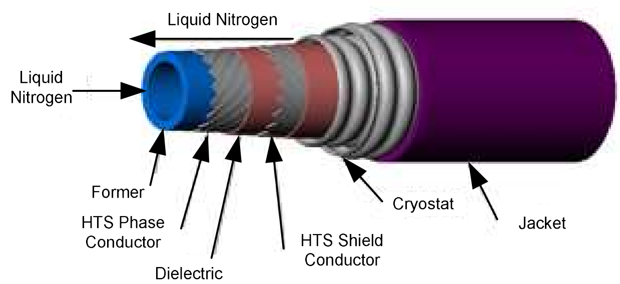


Figure 3 The Cold dielectric (CD) superconducting cable design

The most important parameter of cables are the resistance, capacitance and inductance which effects the power system behavior. The line parameters [17] used for the superconducting cable in this study is given in Table III.

Table 3

The superconductor cable parameters

Resistance (Ω/km)	Inductance (mH/km)	Capacitance (nF/km)
0.0001	0.06	200

4. SIMULATION RESULTS

In this section the simulation results are given for the 3 cases explained in the previous section. Also, the power flow equations and continuous power flow equations that were used in simulations are explained.

4.1. Power Flow and Loss Results

A power-flow study provides information about the voltages, currents, and power flows in a power system under steady-state conditions which are very important information for system planning and control. In this work, the power flow equations of the system was solved by using Newton-Raphson method due to faster convergence through PSAT program in MATLAB. Note that in the power flow studies, Generator 1 is considered as a slack bus.

Power flows in the system are computed by the following set of nonlinear Equations (1)-(6),

$$\Delta P_i = P_{gi} - P_{li} - P_i = 0 \qquad (1)$$

$$\Delta Q_i = Q_{gi} - Q_{li} - Q_i = 0 \qquad (2)$$

$$P_i(x) = V_i \sum_{j=0}^{N_b} V_j (\cos\theta_{ij} G_{ij} + \sin\theta_{ij} B_{ij}) \qquad (3)$$

$$Q_i(x) = V_i \sum_{j=0}^{N_b} V_j (\sin\theta_{ij} G_{ij} - \cos\theta_{ij} B_{ij}) \qquad (4)$$

Active power mismatch equation

$$\Delta P_i = P_{gi} - P_{li} - V_i \sum_{j=0}^{N_b} V_j (\cos\theta_{ij} G_{ij} + \sin\theta_{ij} B_{ij}) = 0 \quad (5)$$

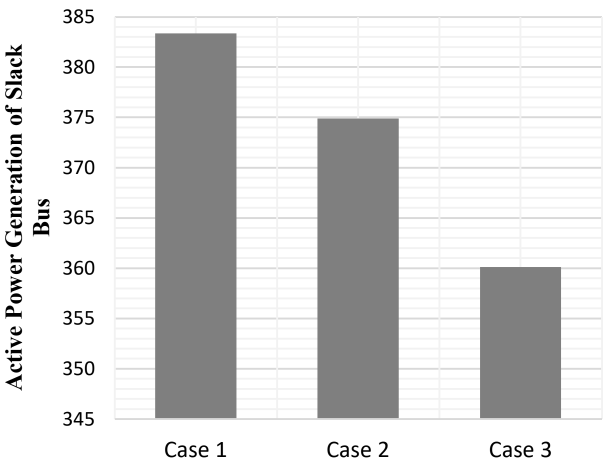
Reactive power mismatch equation

$$\Delta Q_i = Q_{gi} - Q_{li} - V_i \sum_{j=0}^{N_b} V_j (\sin\theta_{ij} G_{ij} - \cos\theta_{ij} B_{ij}) = 0 \quad (6)$$

Where V_i and V_j are the bus voltages and $Y_{bus} = G_{bus} + jB_{bus}$ is the bus admittance matrix, $S_i = P_i + jQ_i$ are the power injections at bus i. P_{gi} and P_{li} is the real power generation and real load at bus i, Q_{gi} and Q_{li} is the real power generation and real load at bus i. The total power loss which is summation of losses of all line sections of the system may be computed as;

$$P_{loss} = \sum G_{ij} \left[V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j) \right] \qquad (7)$$

By the usage of these formulations the power flows between the lines were calculated and the results are given for all 3 cases in Table IV. It can be seen that the direction and amplitudes of the power flows in most of the lines such as line 12, 13 and 14 are changed due to the topologic change of the system.



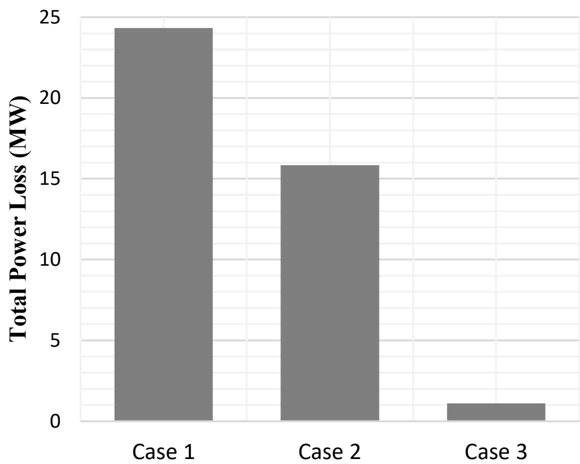


Figure 4 Active power generation of slack bus and total loss of system

Table 4

Line power flows

Line Number	Bus to Bus	Case 1		Case 2		Case 3	
		P (MW)	**Q (MVAr)**	**P (MW)**	**Q (MVAr)**	**P (MW)**	**Q (MVAr)**
1	1-2	182.04	25.498	178.21	25.714	105.78	-270.48
2	2-3	114.88	43.009	113.07	43.206	-187.6	1040.39
3	12-19	-194.2	-237.84	-175.66	-100.77	190.1	-1293.47
4	1-5	201.32	44.894	196.67	45.121	0.081	-1648.37
5	17-6	0.077	-106.02	0.077	-106.02	-302.51	-249.57
6	8-17	-285.11	-111.07	-293.49	-109.53	-37.878	-392.84
7	7-8	-20.458	37.804	-28.838	39.39	-46.474	-129.99
8	9-10	-42.048	0.35	-31.082	-0.973	40.831	-698.78
9	9-11	49.611	-11.111	30.075	-9.051	-248.7	-153.69
10	13-12	-248.7	-153.69	-248.7	-153.69	-413.45	-66.514
11	15-22	-402.93	-132.85	-199.69	-102	170.03	-1240.73
12	2-4	66.416	20.79	-619.62	-319.05	64.205	-129.1
13	12-14	-116.13	24.024	64.425	21.073	-115.46	-300.21
14	20-22	91.484	-163.35	-326.21	-164.5	95.018	-2624.31
15	20-21	-330.52	34.201	-30.668	-150.58	-328.49	-57.786
16	22-21	-170.59	135.34	-414.92	44.281	-173.36	1940.35
17	15-18	-42.344	-103.78	-86.271	124.93	-38.407	-667.6
18	10-18	-183.1	-42.423	-53.387	-76.016	-187.48	605.78
19	14-20	-408.31	-119.72	-172.11	-43.58	-407.46	186.31
20	12-15	-215.58	-110.87	-24.047	-59.336	-222.84	-1050.1
21	4-5	188.66	138.74	184.87	139.4	180.89	-1083.35
22	17-9	312.05	173.93	303.46	174.49	298.36	-791.09
23	4-16	-676.81	-387.81	-676.81	-387.9	-679.92	2147.68
24	3-4	-121.37	-56.852	-123.17	-56.592	-130.22	391.23
25	19-11	155.91	55.376	175.5	53.84	164.18	-815.9
26	5-7	152.61	126.49	144.22	127.92	134.93	-655.11

As shown in Fig. 4, the active power generation of the slack bus which covers all the losses decreases from 383 MW to 375 MW in second and from 383 MW to 360 MW in the third case due to the decrease of the total power losses. The total power loss of the system decreases 34.85% for the second case and 95.5% for the third case. The power that will be needed for the cooling system and the detailed economic analysis of the system is not taken under consideration in these cases which is the planned research in the future. When the cooling system and economic analysis is done it is clear that the decrease percentage of the system losses will not be this effective. But still the usage of such concept is possible in critical situations and special areas/buses/lines.

The presentation of the power losses in lines are in two different scaled axes in Fig. 5. The reason of this is that the amplitude of the losses in Case 3 are much smaller which is not visible if plotted with Case 1 and Case 2.

It can be seen from Fig. 5 that although only one line in the system is changed (Case 2), the system is dramatically affected and the topology of system is altered such as the direction and magnitude of line power flows, critical bus and stability limits. The total power losses and line power loss between 14 and 20 decrease from about 24 MW to 16 MW and from 4.8 MW to 0.12 MW (Fig. 5/Line 19) respectively by changing the line between bus 14 and 20 connected to the critical busses due to small resistance of the superconducting cable line and also reducing the active power flow through the cable from 408 MW to 172 MW.

Also it is well known that when produced from a coal burning plant, 1 kWh of electricity generates 0.94 Kg of CO_2. The usage of superconductor cables saves 6.98x10^{10} and 2.035x10^{11} kg of CO_2 a year in order of Case 2 and 3. This is an important result for a clean environment and green energy.

4.2. Voltage Stability

Voltage stability is an important factor in planning and operating electrical power systems. To maintain the stability of the system some analysis must be done and considered. This section presents the voltage stability analysis of the electrical power system using the voltage-loading factor curve. The curves show us the maximum loadability of the related buses. In order to obtain voltage-loading factor curves, the continuation power flow based on Newton Raphson power flow method is used in PSAT. In the steady-state power flow (continuous flow) analysis, the basic loads in the system are considered as initial and these loads can be increased with a certain load parameter to obtain the changes in the voltage and to reach the PV curves. In continuous-state power flow analysis, the λ-V curves are drawn by $P = P_0(1 + \lambda)$ and $Q = Q_0(1 + \lambda)$. λ -V curves are considered to be PV curves because λ is the variation in loading.

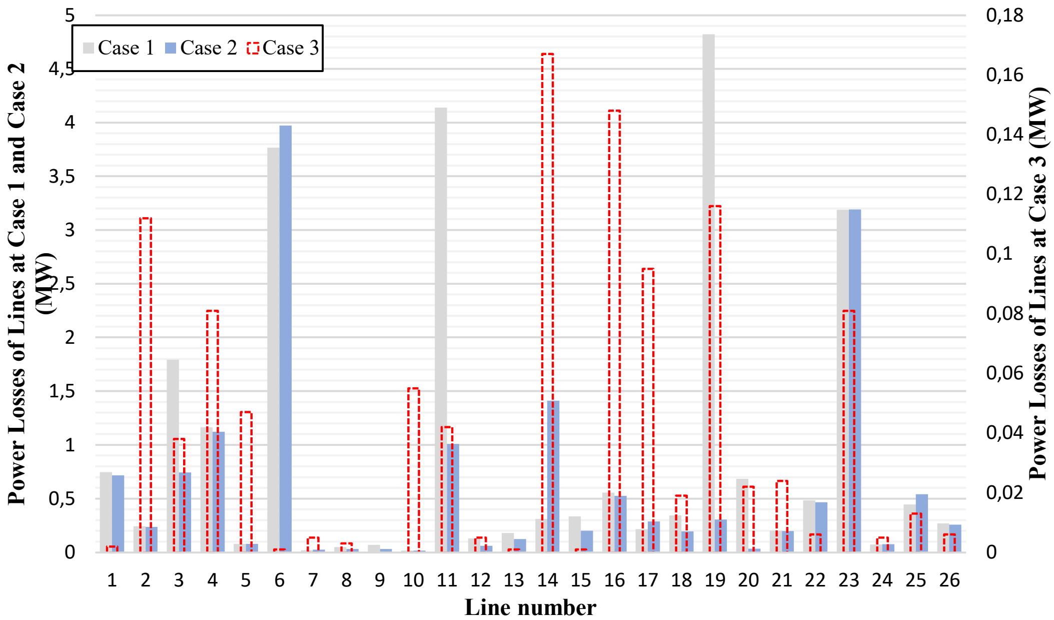


Figure 5 Power losses of lines

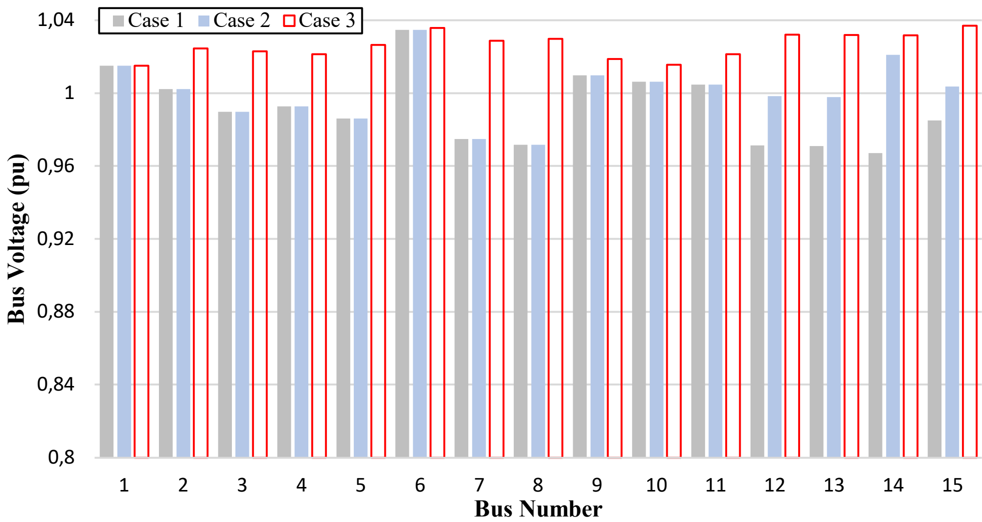


Figure 6 Bus voltages in different cases

One can clearly see that by adding a superconducting line in Case 2, voltages of buses 12-13-14-15 increase while in Case 3 nearly all bus voltages increase. This is an opportunity to work at lower voltage levels. The bus voltages at bus 16,17,18,19,20,21,22 are not given in the Fig. 6, because the voltages at PV generator buses are constant under all cases.

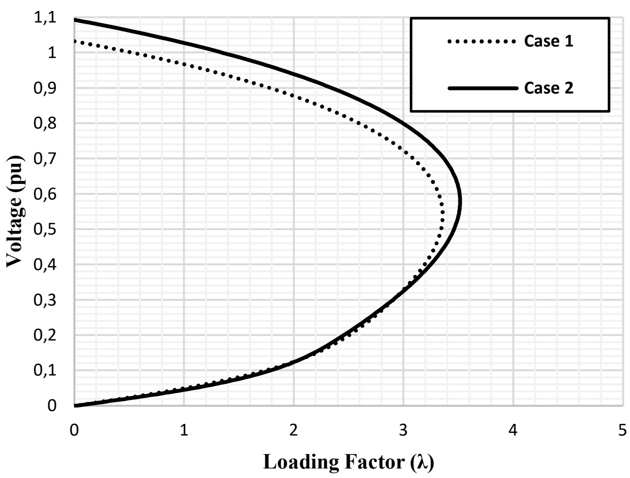


Figure 7 PV curve of Bus 14 in Case 1 and 2

The maximum loading factor (λ) and voltages for each case is given in Table IV. It is seen that when the most charged line in the power system is replaced by a superconducting line, the loading capacity of the critical busbar (the busbar which is most affected by the load increases in the system and which is the closest to the voltage collapse) has increased. And also the critical collapse point of the busbar has increased. With this change, it is seen that the system's ability to withstand sudden disturbance effects or sudden load changes in the system increases.

Table 5

The maximum loading factor and voltage values for the three cases.

Case Number	Max. critic loading factor (λ)	Voltage (pu)
Case 1	3.356	0.5299
Case 2	3.515	0.5726
Case 3	51.592	0.5781

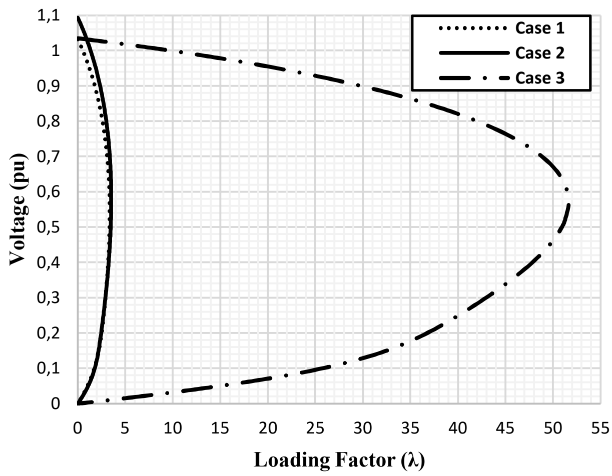


Figure 8 λ-V curve of Bus 14 in Case 1,2 and 3

5. CONCLUSIONS

Power systems face various problems during operating such as overloads, fault currents, voltage sag etc. Superconducting materials offer solutions to these situations with their unique properties. The basic application of superconductors that is almost used in all applications are superconductor cables. A power flow study was presented which is currently used for planning and operating power systems to show their impact on the power system. The Turkish 22 Bus 380 kV system was used. The simulations were carried out at PSAT/MATLAB®.

The results from power flow simulations show the decrease in the active and reactive power losses. In addition to the economic benefits of the reduction in losses, less CO_2 is released due to the decrease in the heat emitted to the environment. Simulation results also show that less energy is needed to feed the same loads, or that more load can be fed with the same production. This can be used as a solution in high populated/large cities, where the need of electricity is increasing rapidly but finding places for new transmission lines and systems are difficult. The need off high current densities in areas like onboard naval ships, data centers and electric aircrafts can be full filled by superconductor cables. Even in Case 2, where only a single conventional line changes with a superconducting line, the values and directions of the currents in the transmission lines changes extraordinary. The change of these currents and directions affects the topology of the system. In addition, power system elements such as breakers/fuses must be replaced according to new current values. In an existing system, changing all of the transmission lines is economically challenging. However, it is obvious that changing the critical transmission line or designing new systems as superconductors with appropriate modeling will be effective.

Transmitting power at high voltage levels influences the current amount and decreases the power losses but on the other hand it increases the cost of substations. Therefore by using superconducting cables in power systems, the voltage level that the power is being transmitted can be re-organized.

It is important to obtain the λ-V curves in power systems and to determine the maximum amount of load that can be transported without collapse. As one can see from results given in section IV (voltage stability), the addition of superconducting cables to the system increases the maximum loading capacity of system which is an important benefit and research has been made to investigate this parameter. Also the critical voltage value at the maximum loading factor increases.

Although this model does not consider the power losses that will be caused from the cooling systems and the ac losses (very small losses caused by frequency, sheet material of superconducting cable etc.), it is now being extended and also a rough economic analysis is being prepared for future study. The economic analyze will provide information of the system installation and maintenance costs. By adding superconducting equipment's to the system some conventional equipment's (transformators etc.) will be removed which will decrease the installation costs and will reduce the cost difference caused by the new technology.

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