Improvement the resilience of the regional power system in Croatia

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***Abstract*—The paper describes the problem of the maintain to the security of a part of the Croatian power system in Istria due to the unexpected unavailability of generation prior to the maximum peak load in the summer 2017. Considered reduced power system security occurs due to unavailability of thermal power plant Plomin and statistically probable outages of the key high voltage line during the summer thunderstorms. Short-term and long-term measures necessary to improve the resilience of the regional power system in Istria are described. The main purpose of these countermeasures is to reduce the risk of black out and to decrease recovery time of the regional power system in Istria if black out occurs. The cost benefit analysis shows the justification and cost-effectiveness of the countermeasures taken to improve the resilience of the affected part of the power system and points to the need to develop measures at the whole power system.**

***Keywords*—power system, security, resilience, countermeasures**

I. Introduction

Safe and reliable supply of electricity is a basic precondition for the functioning and development of society. Due to different reasons, the unavailability of power plants or/and transmission lines in the power system are possible, and it results by less resilience, i.e. less resistance of the system to withstand the disturbance. One of the main tasks of the Transmission System Operator (TSO) is constant concern about maintaining power system security. Since transmission network is highly meshed it has a high level of security of operation and maintaining the n-1 security criterion is an obligation, and it is largely resistant to disturbances. However, in the case of extreme climatic impacts and simultaneous multi-line outages together with unplanned unavailability of generation can cause disturbance in the considered part of the power system. In such situations, the main task of the TSO is to maintain the power system operation with reduced security and timely implement previously prepared measures in order to fast recover of the state of power system to normal for the worst case scenario. In mid-2017 there was unplanned unavailability of whole thermal power plant (TPP) Plomin and it endangered the security of electricity supply in the region of Istria penisola in anticipation of the expected maximum loads of the system during July and August. Since at that time the intense lightning and summer storms in Istria are highly probable which is statistically proven and listed in TSO statistical report [1], together with unavailability of TPP Plomin, black out in Istria during the maximum of touristic season is possible. Due to mentioned facts Croatian transmission system operator prepared short-term and long-term measures before the summer of 2017 in order to maintain the power system security in Istria on satisfactory level with the aim of improving the resilience, i.e. reducing the risk of blackouts and decreasing the recovery of the system in the worst scenario.

II. Description of the Problem

The regional power system of Istria, as shown in Fig. 1, is supplied by electricity from the TPP Plomin with one 105 MW generator(G1) connected to the 110 kV network and with one 210 MW generator (G2) connected to the 220 kV network. With the rest of the Croatian power system, Istria is connected by two 220 kV transmission lines from the Melina and Pehlin hubs and by one 110 kV transmission line. The regional power system of Istria also connected to the Slovenian power system by two 110 kV transmission lines.

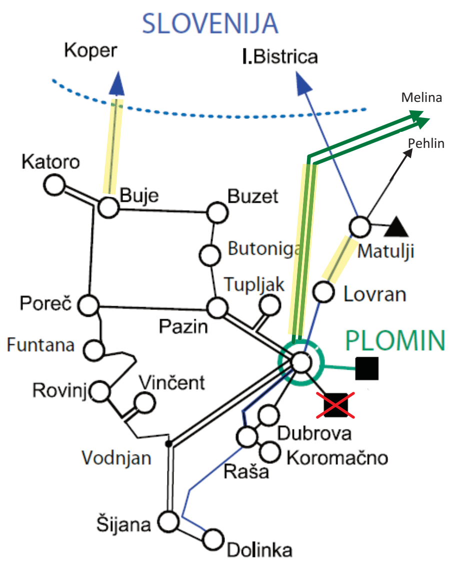

Fig. 1. Regional power system in Istria

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The load of the observed area of Istria varies from 90 MW to 240 MW depending on the season and age of the day (day, night). The peak load occurs during the maximum of tourist season and the highest temperatures in July and August. The peak load coincides with the tourist season peak and the highest temperatures in July and August. In a normal operation, when TPP Plomin and connected transmission lines are available, security of electricity supply to Istria is at a high level. The security criterion n-1 is also fulfilled and the unavailability of any generator, or line, does not endanger the supply of electricity to customers. However, in the case of simultaneous unavailability of G2 in TPP Plomin, loss of both 220 kV line from the Melina and Pehlin hubs,causes the outages of 110 kV lines to Slovenia due to overload which lead to regional black out and interruption of electricity supply.. Previously described event exactly happened on July 12, 2012 as described in [1]. That day at 13:21 hours, due to the extreme thunderstorms and lightning, the outages of connected 220 kV lines and G2 generator in TE Plomin occurred. After the overload of 110 kV lines and their outages the blackout of the regional system of Istria is occurred. The Istrian power system was gradually restored by sectioning of transmission network and the switching of 220 and 110 kV lines. electricity supply in Istria was normalized at 13:58 hours. The analysis of the previously described operational event shows that blackout is possible in the extreme situation when generators in TPP Plomin and the 220 kV transmission lines from the Melina and Pehlin hubs were simultaneous unavailable. An additional unfavorable circumstance is that the connection of 220 kV lines from the Melina and Pehlin direction at the TPP Plomin due to the limited route area are located on the same towers. As described in [2] this part of the route is heavily exposed to lightning strikes. Since the strongest thunderstorms in Istria are most probably at the summer, during the maximum of tourist season, highest temperatures and peak load, in this period is the biggest risk of a blackout of the Istrian regional power system. In this case are the biggest probability and the consequence of blackout due to non-delivered electricity and possible customer complaints.

III. PHASES OF THE RESILIENCE

As described in [3] the critical infrastructure resilience is ability to reduce the magnitude and/or duration of disruptive event. In a normal operating mode, the power system, as described in [4], provides a secure electricity supply to customers. The power system also satisfies security criterion n-1 and the outages of the single production units and/or transmission line should not jeopardize the operation of the system. However, in case of simultaneous unavailability of production units or lines in the transmission network, disturbances and partial blackout of the power system in the worst scenario are possible. Unavailability of production and transmission capacities can be planned (maintenance) and unplanned (failures) and most commonly their combination. Failures of components in the power system can be caused by internal and external reasons. In consideration of the resilience, as described in [5] and visible in Fig. 2, the following phases are distinguished:

A. Initial phase – pre-disturbance time (T_A)
B. Phase of disturbance - time of disturbance (T_B)
C. Restoration phase – time of restoration (T_C)
D. Resilience improvement phase – time of recovery (T_D)

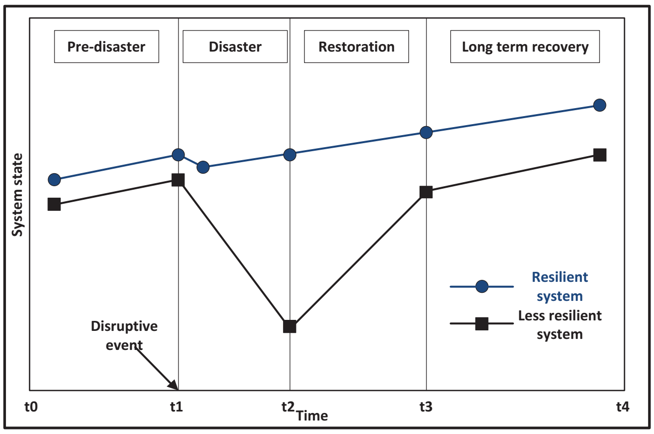

Fig. 2. Phases of the power system resilience

The initial phase is the state of existing power system before the disturbance, whereby the system functions in the normal operating mode and satisfies the criterion n-1. As described in Chapter II, disturbance in the power system can be caused by internal and external reasons and may result by unavailability of production and transmission capacities in a specific part of the power system. Depending on the extent and duration of unavailability of mentioned capacities, it will function with reduced security, and in extreme cases, the disturbance in the power system may occur. In the phase of the disturbance, there is a decrease of the power system security and after the end of the incident; the resilience will be at lowest level. Subsequently, the system recovery phase is followed by the gradual switching of the production units and transmission lines in operation and the establishment of system status and resilience in proportion to their availability. As described in [6] effectiveness of a power system's resilience depends on its ability to adapt, and rapidly recover from a possible disruptive event. The direct consequence of the adverse event is the failure and unavailability of production and transmission capacities, which can lead to reduced system's security and, in the worst case, an interruption of the electricity supply. Due to resilience analysis according to Fig. 2, the duration of each phase and the system status regarding to security is considered as follows:

$$T_A = t_1 - t_0 \tag{1}$$

$$T_B = t_2 - t_1 \tag{2}$$

$$T_C = t_3 - t_2 \quad (3)$$

$$T_D = t_4 - t_3 \quad (4)$$

The onset of the disturbance is the direct impact of an external or internal factor on the power system that causes a failure of production and/or transmission capacity and their unavailability. Depending on the type of failure (transient, persistent) and their number and duration, during the time of disturbance, a sudden decreasing of security and resilience of the power system is possible including extreme system disruption-blackout. After the phase of the disturbance is over, the system restoration phase begins. Based on previously prepared scenarios and procedures the affected area is isolated and production units and transmission lines switch on gradually until to whole system be recovered, if it is possible. If the cause of the disturbance was transient (e.g. stormy weather) and there were no major failures, the system recovery time will be relatively short and after rapidly restoring of the power system the resilience level will be the same as before the disturbance. If permanent failures of production and/or transmission capacities has occurred during the disturbance, due to their unavailability the level of resilience will decrease compared to the state before the disturbance. Based on the above described it can be concluded that it is of particular importance that the time duration of the disturbance (T_B) and recovery time of the power system (T_C) and their sum (T_B+T_C) are as short as possible with an impact on system state as lower as possible. In this way, the level of resilience and security of the power system will be achieved and the negative consequences will be reduced in short time. The analysis of power system performance during disturbance and its recovery will be base for identify of the measures to improve security and resilience in short time and long term framework (T_D).

IV. IMPROVENMENT OF THE RESILIENCE

Assessment of the power system security in Istria during the summer of 2017 showed a significant risk due to reduction of resilience in extreme climatic situation. Disruptive event is simultaneous outage of 220 kV line Melina –Plomin and Pehlin – Plomin which are constructed partially on the same tower. Based on previously mentioned, Croatian transmission system operator has developed short-term and long-term measures to maintain power system security and its resilience to disturbance. The basic principle of power system resilience is visible in Fig. 3. The resilience of the existing power system depends most on the availability of its components. In case of a disturbance, the system will recover after some time depending on its intensity and consequences. Resilience analysis will identify short-term and long-term measures to improve resilience of the power system against incidents. The main goal of the short-term measures was to prevent the simultaneous outages of both transmission lines 220 kV close to TPP Plomin in the event of thunderstorm, enlarge time T_B), in order to give a possibility to dispatcher to react end reduce system state detoriation (Y-axis on Fig. 4) and reduce the time for restoration and recovery of the system (T_C), if outages of the above mentioned transmission lines and the blackout of the Istrian power system occurred. Based on the analysis of the simultaneous outages both 220 kV line in the critical zone from the past, adequate relay protection settings have been made in order to prevent a simultaneous outages both of line due to outages only one of them. In cooperation with the neighboring Slovenian transmission system operator of the relay protection system 110 kV cross-border lines are also set for possible increased loads.

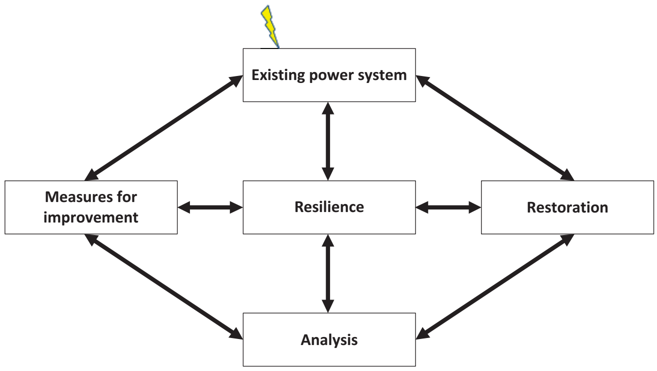

Fig.3. Principle of resilience

Since the outages of both 220 kV transmission lines, which are crucial for the supply of electricity to Istria is still possible, further analysis have been made to minimize the time of power system restoration in case of blackout. In this regard, specific procedures have been prepared to shorten the time to switch on certain consumption areas in Istria as much as possible, as indicated as variable T_C,. With this intent, the Regional Network Control Center in Rijeka continuously monitored the meteorological situation in the region. In the case of unfavorable weather forecasts, an alarm was detected and emergency personnel were sent to substations due to restore of the power system after blackout as soon as possible.

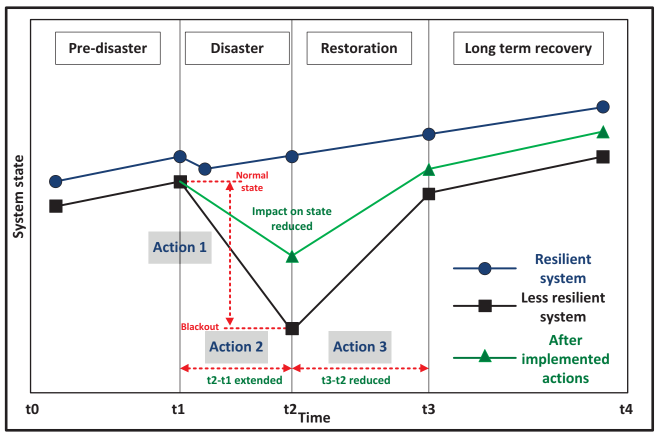

Fig. 4. Improvement of resilience of Istrian power system

During the summer of 2017, the Network Control Center in Rijeka twice activated the meteorological alarm for Istria region and sent emergency personnel to critical substations in the Istrian network. Fortunately, thunderstorms did not cause the outages of the 220 kV lines close TPP Plomin and the possible disturbance of the Istrian power system. By short-term measures outlined above is decreased the probability of the blackout and the time of power system recovery of the power after disturbance (T_C), thus directly increasing the system's resilience as shown in Fig. 4. The main goals of the long-term measures for improving the resilience are: adequate protection of existing 220 kV lines against lightning as described in [2], increase the efficiency of 110 kV lines and construction of new 220 kV transmission line in region. These long-term measures to increase the resilience of the Istrian power system will be additional arguments for the development plan and investment in the Croatian transmission network. After implementation of the long term measures resilience of the regional power system in Istria in case of extreme climatic impact during the summer as visible in Fig.4, will be on higher level than before and risk including its consequences due to blackout will be significantly reduced.

V. COST BENEFIT ANALYSIS

The cost benefit analysis (CBA) is performed on examples of implementation of measures to improve the resilience of Istrian power system. The unsupplied energy to customers (W_{us}) is calculated according to the formula

$$W_{us} = \sum_{i=1}^{m} W_{usi} \tag{5}$$

where i=1,…m is a number of particular outages.

Direct and indirect costs are calculated based on hypotetical, previously described disruptive event, outages of both 220 kV transmission lines near TPP Plomin in the summer of 2017 at the maximum load of 240 MW and the unavailable TPP Plomin. This hypotetical event causes blackout and further restoration and recovery of the power system. Presumed duration of blackouts is 1 hour and 30 minutes. The CBA results for the example of short-term measures to improve the resilience are shown in Table I. The unsupplied energy for the assumed system restore time calculated according to expression (5) is 240 000 kWh.

TABLE I COST BENEFIT ANALYSIS (SCM)

Cost (euro)	Duration of black out (h)	
	1	*0,5*
Direct TSO cost	4[a]	2
Indirect TSO cost	170-340	85-170
Emergency personal cost	2	6
Total	176-346	93-178

The direct cost of the system operator because of the unsupplied energy is calculated according to the actual tariffs. Indirect cost due to unsupplied energy to customers is calculated with the assumed factor 5-10 that multiplies the price of unsupplied energy to customers. The implementation of short-term measures to improve the resilience of the regional power system of Istria described in Chapter IV caused additional costs, and the presumed time of recovery of the system for the introduction of a special procedure after the announcement of the weather alarm (T_C) is 30 minutes. Thus, the possible total costs due to the outages of the 220 kV transmission lines would be doubled, and thereby the risk of the blackout was twice smaller than before. It will be also analyze the implementation of one of the long-term measures to improve the resilience of the Istrian power system described in Chapter IV, which concerns the improvement of the protection of 220 kV lines against lightning. By installing line surge arresters (LSA) on the most jeopardized towers, the lines near TPP Plomin will be efficiently protected against lightning and the risk of their outages will be much smaller than before. Investment in the installation of LSAs that will permanently protect the mentioned lines from the lightning and outages is about 600 thousand euros. The results of cost benefit analysis due to implementation of long-term measures to improve the resilience of Istrian power system are shown in Table II.

TABLE II COST BENEFIT ANALYSIS (LTM)

Cost (euro)	Duration of blackout (h)	
	0,5	*0*
Direct TSO cost	2[a]	-
Indirect TSO cost	85-170	-
Emergency personal cost	6	-
Installatio on LSAs		600
Total	93-178	600

Previously described investment is justified since it is at the same cost level as costs of three blackouts of Istrian regional system and permanently reduces the risk of the outages 220kV transmission lines and appropriated costs due to lightning. By implementation the described long-term measures, the time to improve the resilience (T_D) will be reduced, thus the risk of blackout and all its consequences. The implementation of the remaining long-term measures to improve the resilience of the Istrian transmission network (replacement of 110 kV conductors, construction of a new 220 kV transmission line) requires significant investments and should be considered within the framework of the future Croatian network development plan.

VI. CONCLUSION

Security of the power supply is a key precondition for the functioning and development of society. Due to unexpected unavailability of generation and statistically probable outages of the key high voltage lines caused by lightning, security and resilience of the Istrian power system before summer 2017 peak load was directly jeopardized. Resilience analysis identified short-term and long-term measures to improve resilience of the power system against incidents. The main goal of the short-term measures was to prevent the simultaneous outages of the key lines 220 kV due to lightning and minimize the time of restoration and recovery of the Istrian power system if the mentioned outages of the lines and the blackout happen. The cost benefit analysis proved the justification of the measures taken to improve the resilience of Istrian power system. The experience in improvement the resilience of the Istrian power system will be useful for considering the resilience of other regions and the whole Croatian power system.

VII. LITERATURE

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