FORMALIZING POWER GRID INFLUENCE TO ASSESS THE SAFETY OF NUCLEAR POWER PLANTS

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Abstract: After the Fukushima nuclear accident the problem of safe interaction between a nuclear power plant and the power grid requires urgent attention. The Ukrainian power grid is the backbone for stable development of all dependent infrastructures. Nuclear power plants can be seen as elements interacting with the system for power distribution. There are five nuclear power plants (NPP) in Ukraine. The NPP safety depends on the reliability of its subsystems, components, etc., as well as on the safety levels of other power grid subsystems. There are various interdependencies among NPPs and the power grid, which impact the safety levels of both. The balance of these mutual influences is considered as a basis for the stability of any infrastructure. The change of influences could lead to violation of the balance, that in turn may lead to a change in the subsystem's state. This paper presents an approach for formalization of different types of influences between dependent infrastructures. This approach supports the analysis of the behaviour of infrastructure subsystems and the prediction of their safety levels, considering the change of states. Two metrics are proposed to evaluate the influences: linguistic and numerical. The influence formalization enhances the understanding of risk proliferation and the assurance of NPP safety.

Keywords: Power grid safety, nuclear power plant, NPP, impact, influence, formalization, risk assessment.

Introduction

The Ukrainian energy sector is of key importance for the national economic development, as both production and municipal facilities require electric power for their operation.[1] The Ukrainian power industry consists of power generating system, high voltage transmission system, lower voltage distribution system and other support facilities.

Three types of generation facilities are operated in Ukraine, including thermal power plants (steam turbine and diesel types), hydroelectric plants (hydroelectric proper and hydroelectric accumulating plants) and nuclear power plants. Thermal power plants account for about 50% of the electric power produced in Ukraine. Most of these thermal power plants are old, with antiquated equipment, obsolete technology, and largely lacking modern pollution control equipment. Only about 10% of Ukraine's thermal power plants had undergone any significant reconstruction.

Some 250 thermoelectric plants operate in the country. The major fuel for the plants is natural gas (76-80%), but they also use black oil (15-18%), and coal (5-6%). Most steam power plants have outdated equipment which does not correspond to present-day environmental requirements, and calls out for reconstruction, upgrade, or complete replacement. Ukraine's five nuclear power stations operate 15 reactors with a capacity of 12.3 giga watts (GW), or nearly one-quarter of the country's total. They generate around 88,8 GW of energy, or over 47.9% of the country's power output, with the construction of two reactors with a capacity totalling 2 gigawatts (GW) in its final stages.

The basic internal causes which lead to disturbances of the power grid's operational mode:[2]

- stable short circuit on the high-voltage transmission lines followed by their removal from service (50-70 percent out of all power grid accidents) (causing the blackout in 2003);
- short circuits which stipulate the activation of differential bus protection (more than 10 percent);
- emergency shutdown of the power block (nearly 5 percent);
- staff's errors (nearly 5 percent).

Among the basic external causes leading to disturbances of the power grid's operational mode are seismic vibration; wind influences on power grid's facilities; icing on transmission lines (quite frequent in Ukraine); natural disasters such as fires, flooding, hurricanes, pollutions.

Grid interconnectivity and redundancies in transmission paths and generating sources are key elements in maintaining reliability and stability in high performance grids. However, operational disturbances can still occur even in well maintained grids. Similarly, even an NPP running in baseload steady-state conditions can encounter unexpected operating conditions that may cause transients or a complete shutdown in the plant's electrical generation. When relatively large NPPs are connected to the electric grid, abnormalities occurring in either can lead to the shutdown or collapse of the other.

In addition to assuring that the electric grid will provide reliable off-site power to NPPs, there are other important factors to consider when an NPP will be the first nuclear unit on the grid and. most likely, the largest unit. If an NPP is too large for a given grid, the operators of the NPP and the grid may face several problems.

Off-peak electricity demand might be too low for a large NPP to be operated in base load mode, i.e. at constant full power.

There must be enough reserve generating capacity in the grid to ensure grid stability during the NPP's planned outages for refuelling and maintenance.

Any unexpected sudden disconnect of the NPP from an otherwise stable electric grid could trigger a severe imbalance between power generation and consumption causing a sudden reduction in grid life.

The technical issues associated with the interface between NPPs and the electric grid include:[3]

- The magnitude and frequency of load rejections and the loss of load to NPPs;
- Grid transients causing degraded voltage and frequency in the power supply of key safety and operational systems of NPPs;
- A complete loss of off-site power to an NPP due to grid disturbances;
- An NPP unit trip causing a grid disturbance resulting in severe degradation of the grid voltage and frequency, or even to the collapse of the power grid.

Influence of grid disturbances on nuclear power plants

Load rejection and complete loss of load

A load rejection is a sudden reduction in the electric power demanded by the grid. Such a reduction might be caused by the sudden opening of an interconnection with another part of the grid that has carried a large load. An NPP is designed to withstand load rejections up to a certain limit without tripping the reactor. An NPP's ability to cope with a load rejection depends on how fast the reactor power can be reduced without tripping and then how fast the reactor power output can be increased hack to the original level when the fault is cleared. Load rejections of up to 50% are accommodated by a combination of several actions: rapidly running back the steam turbine to the new lower demand level, diverting the excess steam from the turbine to the main steam condenser unit or to the atmosphere if this is permitted by licensing regulations, and reducing reactor power via insertion of control rods without tripping the reactor.

A *loss of load* is a 100% load rejection, that is the entire external load connected to the power station is suddenly lost, or the breaker at the station's generator output is opened.

Degraded grid voltage or frequency

Electric grids are controlled to assure that a particular frequency, either 50 or 60 Hz, is maintained within a small tolerance, typically within ± 1%. When the grid develops an imbalance between generation and load, the grid frequency tends to 'droop' if the load exceeds generation and increase if generation exceeds the load. A reduction in frequency can be caused by several events, such as insufficient available generation, a major electrical disturbance such as a circuit fault or the trip of a major generator unit. A small droop in the grid frequency caused by the loss of generation can be controlled by quickly activating the grid's available 'spinning reserve", either automatically or manually, starting up additional generation capacity, such as gas turbines or hydroelectric power, and disconnecting selected loads (i.e. customers) from the grid (load shedding).

Loss of off-site power

Any loss of off-site power would he caused by external events beyond the NPP's switchyard, such as transmission line faults and weather effects like lightning strikes, ice storms and hurricanes. A loss of off-site power interrupts power to all in-plant loads such as pumps and motors, and to the NPP's safety systems. As a protective action, safety systems will trigger multiple commands for reactor protective trips (e.g. turbine and generator trip, low coolant flow trip, and loss of feedwater flow trip). The reactor protection system will also attempt to switch to an alternate off-site power source to remove residual heat from the reactor core. If this fails, in-plant electrical loads must be temporarily powered by batteries and stand-by diesel generators until off-site power is restored. However, diesel generators may not be as reliable as off-site power from the grid in normal conditions. Diesel generators may fail to start or run 1 % of the time. However, the probability of failure can be significantly reduced by installing independent trains of diesel generators. Batteries can provide power only for a limited time.

Influence of grid disturbances on nuclear power plants

Trip of an NPP causing degraded grid frequency and voltage

Even at steady state conditions, when the generation and loads on a grid are in balance, if a large NPP (e.g. 10% of the grid's total generating capacity) trips unexpectedly, the result can be a significant mismatch between generation and load on the grid. Unless additional power sources are quickly connected to the grid, this can degrade the grid's voltage and frequency and thus the off-site power supply to the NPP. The degraded voltage and frequency on the grid can potentially result in the NPP protection system disconnecting the degraded off-site power to the NPP. This will force the NPP to switch to on-site emergency power to run safety and core cooling systems until off-site power is restored. This should be done as soon as possible for safety reasons: the possible concurrent failure of the NPP's on-site power system and delayed recovery of off site electric power would make it nearly impossible in most NPPs to cool the core, a situation that must he avoided under all conditions. The introduction of new reactor designs that use passive cooling would alleviate this problem. Therefore, in unreliable grid systems. it is recommended to consider NPP designs with passive safety systems.

Types of influences

The NPP as a part of power grid (PG) constantly interacts with other elements of PG. All influences (or relationships) existed in PG could be divided into several hierarchy's levels. The first level of hierarchy is a level of interaction between NPPs and TPPs, HPs as other generating systems. They could interact indirectly by means of transmission and distribution networks. On this hierarchy's level systems influence each other as a whole. Generally influences could be classified into different types:[4]

1. Physical $I_{phys}^{NPP}(t)$ - a physical reliance on materials flow from one infrastructure to another. This physical reliance could be of two types: internal and external. The internal reliance refers to electrical flow between NPP and other PG's elements. The external reliance refers to PG's interactions with other infrastructures. For example a thermal power plant generating 1,000 mW typically consumes 10 000 tons of coal per day. Under normal operating conditions the PG requires natural gas and petroleum fuels for its generators, road and rail transport and pipelines to supply fuels to generators, water for cooling and emissions control, banking and finance for fuel purchases etc.

2. Informational $I_{\inf}^{NPP}(t)$ - a reliance on information transfer between NPP and other elements of PG (via through I&C systems). NPP-PG state depends on information transmitted through the information infrastructure. Informational dependencies connect NPP and other PG elements via electronic, informational links.

3. Geographic $I_{geo}^{NPP}(t)$ - a local environmental event affects components of NPP-PG (usually the transmission lines) due to physical proximity; Given this influence, events such as an explosion or fire could create correlated disturbances or changes in these NPP-PG elements.

4. Logical $I_{log}^{NPP}(t)$- an influence that exists between NPP - PG that does not fall into one of the about categories. Logical dependencies may be more closely likened to a control scheme that links PG's elements without any direct physical, informational, geographical connections (all indirect influences, example – Moscow blackout 2005 resulted to banking systems disturbances).

5. Organizational $I_{org}^{NPP}(t)$ (influences though policy, regulation, markets). The influence that exist due to policy or procedure that relates a state change in one elements of PG to subsequent effect on another components;

6. The societal influence $I_{soc}^{NPP}(t)$ that PG components may have on societal factors as public opinion, fear and confidence.

There are some influence types on lower levels of NPP-PG's hierarchy. All influences of subsystem's level might be divided in following categories:

- Functional influence. Connected equipment encompasses NPP and other PG's elements design involving shred equipment, common input, loop dependencies plus situations in which the same equipment provides multiple functions. Non-connected equipment encompasses interrelated success criteria such as the relationships between standby system and the system it is supporting;
- Cyber influences via control systems;
- Spatial influences. Refers to equipment within small distance to each other;
- Human influences . Refers to all activities with human participation.

Influences formalization

As we could see there are a lot of different types of influences which exist on all NPP-PG hierarchy's levels. Though these dependencies create opportunities they also create vulnerabilities. These vulnerabilities may produce adverse impacts that are becoming more widespread and more frequent.

The influences between different systems of PG could be described (or formalized) by means of the Influence vector. The Influence vector is characterized by the value of influence and direction. The direction points the initial source of influence and systems are under influence. The value characterizes the strength of influence.

The influences between NPP and PG elements could be represented by matrix of influence shown in the table 1:

Table 1. Matrix of influence

	NPP	*TPP*	*HPP*
NPP	-	M	H
TPP	L	-	
HPP	M		-

The influence matrix shows how elements of system influence each other and strength of their influence. As an example, NPP influences TPP with a strength – medium and HPP with high level of influence. Generally, influence is an ability of one system to determine the state, characteristics and behavior of other systems.

To evaluate the influences between dependent infrastructures we need to have the metrics by which this influences could be measured and compared. We introduce two types of metrics: linguistic and numerical. The linguistic metric operates with the linguistic values used to evaluate the strength of influence. The different values as high, medium and low are applied to consider and predict the state changing of one infrastructure provided the accident in other infrastructure. Numerical values as ranks are used in the similar way, the different ranks stand for the different strength of influence.

Space of influence

NPP could influence the power grid in the different ways as physically, geographically, organizationally, by means of information, logically, societal. Thus we could introduce the space of influence. Physical, geographical, organizational, informational, logical, societal is a particular influence. Total influence might be represented as:

$$I_t^{NPP}(I_{geo}^{NPP}(t), I_{phys}^{NPP}(t), I_{org}^{NPP}(t), I_{soc}^{NPP}(t), I_{log}^{NPP}(t)). \tag{1}$$

The total influence is a time dependable value. The changes of NPP states and characteristics stipulate the changes of the total influence value. We could illustrate the particular influence, for example geographical influence of NPP on other system of power grid (SPG) shown in Figure 1.

Formally, the geographical influence of NPP on other systems of power grid (SPG) might be written as:

$$\overline{I}_{geo}^{NPP}(t) = \left\{ \overline{I}(NPP \to TPP), \overline{I}(NPP \to HPP), \overline{I}(NPP \to TG) \right\} = \\ = \{Medium(M), High(H), Low(L)\}. \tag{2}$$

The value of geographical influence could be calculated as:

$$I_{geo}^{NPP} = \sum_{i=1}^{I} I_{geo}^{i}(NPP \to SPG_i) = H + M + L. \tag{3}$$

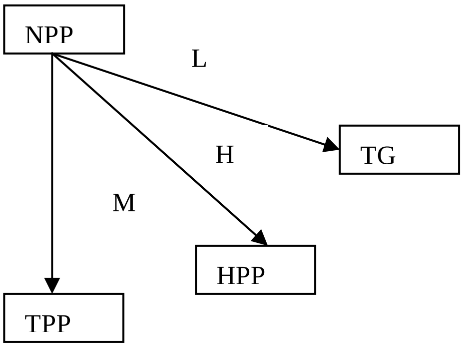

Figure 1: Geographical influence.

Similarly, the organizational influence might be represented in Figure 2.

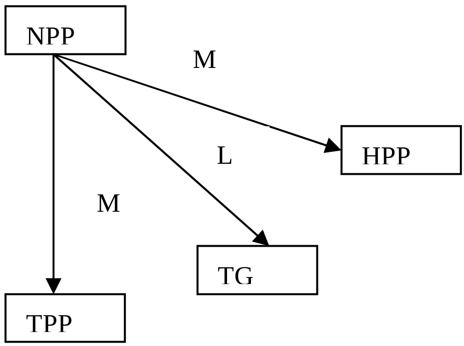

Figure 2: Organizational influence.

The value of organizational influence could be calculated as:

$$I_{org}^{NPP} = \sum_{i=1}^{I} I_{org}^{i}(NPP \rightarrow SPG_i)\,; \tag{4}$$

$$I_{org}^{NPP} = \sum_{i=1}^{I} I_{org}^{i}(NPP \rightarrow SPG_i) = M + L + M.$$

The total influence value might be calculated as a sum of the particular influence values on all influence space existed for NPP-PG system. The total influence value calculated as a sum of the particular influence values characterizes the absolute influence of NPP on other SPG. For each systems of power grid could be evaluated their total influences. Their ranking might determine the most and least influential system. In table 2 the different influences' factors are combined.

Table 2. The combined matrix of influences.

	Physical				***Geographical***				***Informational***			
	NPP	TPP	HPP	DG	NPP	TPP	HPP	DG	NPP	TPP	HPP	DG
NPP	0	M	L	H	0	H	M	L	0	M	H	M
TPP	M	0	M	L	H	0	M	L	H	0	H	H
HPP	L	H	0	H	H	L	0	H	H	L	0	H
DG	L	L	H	0	L	M	M	0	L	M	H	0

It could help to estimate the value of total influence, for instance, NPP on all of subsystems as:

$$
\begin{aligned}
&I_{tot}^{NPP}(I_{phys}^{NPP}(t), I_{geo}^{NPP}(t), I_{org}^{NPP}(t), I_{inf}^{NPP}(t),\ldots, I_{soc}^{NPP}(t)) - total\ NPP's\ inf\ luence;\\
&I_{phys}^{NPP}(t) = \sum_{i=1}^{I} I_{phys}^{i}(NPP \to SPG_i);\ I_{geo}^{NPP}(t) = \sum_{i=1}^{I} I_{geo}^{i}(NPP \to SPG_i),\ldots;\\
&I_{tot}^{NPP} = w_{phys}(H+M+L) + w_{geo}(M+L+H) + w_{org}(M+H+L)+\ldots,\\
&SPG_i - S_i\ of\ \ power\ grid.
\end{aligned}
\tag{5}
$$

We shall consider the relative influence value $I_{rel}(t)$. The relative influence value determines the influence of one system on another system, for example NPP on TPP. It might be calculated as:

$$
\begin{aligned}
&I_{rel}(NPP \to TPP) = I_{geo}(NPP \to TPP) + I_{org}(NPP \to TPP) +\\
&\ldots + I_{soc}(NPP \to TPP).
\end{aligned}
\tag{6}
$$

The different types of NPP relative influence are shown in Figure 3. Similarly, for NPP might be evaluated the relative influences of different SPGs. The different influences on NPP shown in Figure 4.

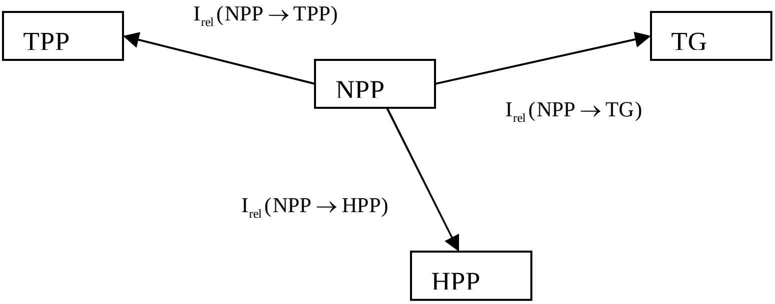

Figure 3: Relative influences of NPP.

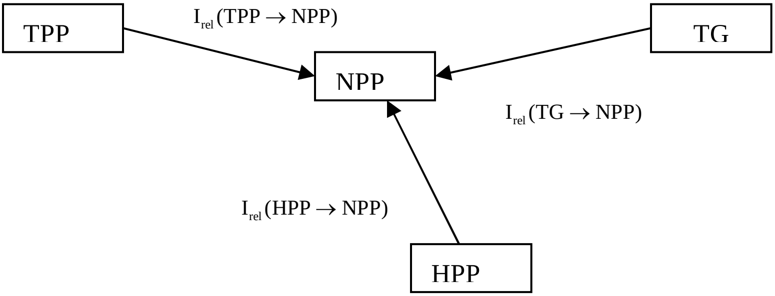

Figure 4: Relative influences on NPP.

It is worth to note that

$$I_{tot}^{NPP} = \sum_{i}^{I} I_{rel}(NPP \rightarrow SPG_i)\,. \tag{7}$$

It might be suggested that stability of the NPP-PG system is provided by the balance of influences between its elements. The principle of infrastructure balance could be taken as one of major principle infrastructure safety assurance. The state dynamic is conditioned by changing of balance of influences insight the system. The violation of balance leads to state changing of infrastructure subsystems. According to principle of hierarchy any system is a part of other system. One system S_1 influences another system S_2 with $I_{rel}(S_1 \rightarrow S_2)$. In the case when this value exceeds the certain value $I_{rel}^{lim}(S_1 \rightarrow S_2)$ it might lead to state changing of S_2. The Fukushima nuclear accident proves this assumption. The NPP might stand the defined value of nature's influence. The earthquake that hit Japan was several times more powerful than the worst earthquake the nuclear power plant was built for (the Richter scale works logarithmically; for example the difference between an 8.2 and the 8.9 that happened is 5 times). In the Fukushima nuclear accident the anticipated value of influence was exceeded what resulted to accident. Let consider the infrastructure shown in Figure 5.

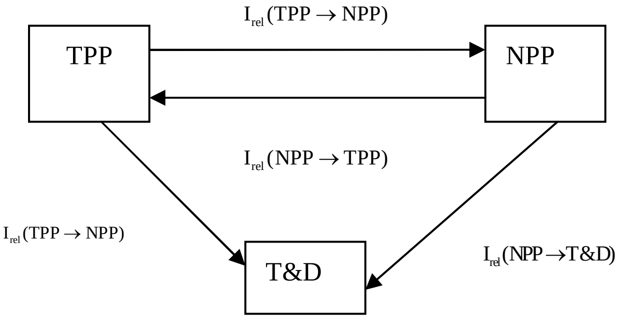

Figure 5: Infrastructure (general).

The infrastructure on Figure 5 could be characterized by some values shown in table 3.

Table 3. The characteristics of influences.

Relation	***Current Influence***	***Influence limit***
$TPP \rightarrow NPP$	$I_{rel}(TPP \rightarrow NPP)$	$I_{rel}^{\lim}(TPP \rightarrow NPP)$
$TPP \rightarrow T\,\&\,D$	$I_{rel}(TPP \rightarrow T\,\&\,D)$	$I_{rel}^{\lim}(TPP \rightarrow T\,\&\,D)$
$NPP \rightarrow T\,\&\,D$	$I_{rel}(NPP \rightarrow T\,\&\,D)$	$I_{rel}^{\lim}(NPP \rightarrow T\,\&\,D)$
$NPP \rightarrow TPP$	$I_{rel}(NPP \rightarrow TPP)$	$I_{rel}^{\lim}(NPP \rightarrow TPP)$

In this case the conditions of safety infrastructure given above based on balance of influence might be written as:

$$\begin{aligned} &I_{rel}(TPP \to NPP) \le I_{rel}^{\lim}(TPP \to NPP);\\ &I_{rel}(TPP \to T\&D) \le I_{rel}^{\lim}(TPP \to T\&D);\\ &I_{rel}(NPP \to T\&D) \le I_{rel}^{\lim}(NPP \to T\&D);\\ &I_{rel}(NPP \to TPP) \le I_{rel}^{\lim}(NPP \to TPP). \end{aligned} \quad (8)$$

When current value of influence between infrastructures exceeds the acceptable value it could result to the state changing of one of them. The Fukushima nuclear accident proved this principle of balance influence. The nature should be considered as subsystem which influences other infrastructures. Other example of result of balance violation consequences is the Sayano-Shushenskaya HPP accident when it couldn't withstand the increasing of load passed from Bratskaya HPP.

The formalization of influences between infrastructures might be helpful for NPP safety analysis based on FMECA. The traditional FMECA [5] is the most widely used reliability analysis technique in the initial stages of system development. It is performed to assure that all potential failure modes have been considered. Traditionally the criticality assessment is performed by calculating the failures criticality as a product of failure severity and frequency:

$$Crt(S_i) = Fr(S_i) \times Sev(S_i), \quad (9)$$

where S_i – infrastructure accident, $Fr(S_i)$ – accident frequency; $Sev(S_i)$ – severity of accident consequences.

The traditional FMECA is two dimensional. In the case when $Crt(S1)=Crt(S2)$ we need to use additional information to differ possible accidents. Therefore the total influence $I_{tot}^{S_i}$ characterized by direction and strength might be used as third value to prioritize the possible accident. The criticality is assessed as

$$Crt(S_i) = Fr(S_i) \times Sev(S_i) \times I_{tot}^{S_i}. \quad (10)$$

Taking into consideration the mutual influences between infrastructures we assume the failure criticality of one infrastructure might be changed as a result of the criticality changing of other infrastructure. We introduce the conditional criticality presented as

$$I\ (S_i^* \to S_j): Crt(S_i \left| S_j^*) = Fr(S_i \left| S_j^*) \times Sev(S_i \left| S_j^*) \right.\right.\right. \quad (11)$$

where $Crt(S_i \left| S_j^*) \right.$ - conditional criticality of S_i provided the failure of S_j^*; $Fr(S_i \left| S_j^*) \right.$ - S_i frequency changing provided the failure of S_j^*; $Sev(S_i \left| S_j^*) \right.$ S_i severity changing provided the failure of S_j^*.

Conclusion

The safe operation of NPP requires that power grid operates in safe manner. It means mutual influences between them should be manageable and predictable. To understand the nature of influence between infrastructures we introduce the approach for formalization based on application the influence matrix. The influence formalization might be very useful for nuclear power plant safety assessment. The influence might be useful for risk analysis based on FMECA as the additional information to compare the possible failures criticalities. The conditional criticality complements the traditional criticality assessment and considers the mutual failures criticality changes. Using the different metrics we could evaluate the strength of influence. The principle of influence balance was suggested as one of principles of infrastructure safety assurance.

Notes:

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