RELIABILITY EVALUATION OF DISTRIBUTION ARCHITECTURES CONSIDERING FAILURE MODES AND CORRELATED EVENTS

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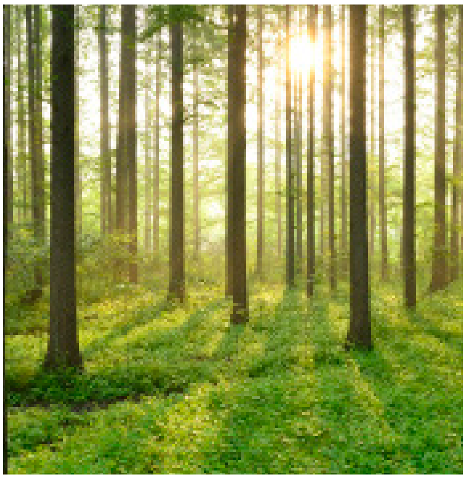

RISK- OCH TILLFÖRLITIGHETS-ANALYS

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Reliability Evaluation of Distribution Architectures Considering Failure Modes and Correlated Events

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Förord

Kontroll- och skyddssystem har studerats tillsammans med primärutrustning ur risk- och tillförlitlighetsperspektiv med målet att utveckla och utvärdera metoder för enhetlig riskanalys. Resultatet har medfört ökad kompetens, ekonomisk effektivitet genom att göra lämpliga design- och teknikval.

Detta projekt är riktat mot att använda riskanalysmetoder utvecklade för primärutrustning på både primär och sekundär utrustning i elnäten. Till att börja med kommer metoder från följande områden användas; risk-, tillförlitlighets- och ekonomisk analys samt i förlängningen investerings- och underhållsoptimering.

Förenklat så studeras i dagsläget primärutrustningen för sig och mät- och styrutrustning för sig inom forskningen. Detta leder till att beslut baserade på denna forskning inte fullt ut tar hänsyn till den ”andra” delen av nätet och att investeringarna i förlängningen inte blir helt effektiva. Genom att studera dessa båda delar samtidigt är målet att nå mer effektiva investeringar med avseende på låg risk till så låg kostnad som möjligt. Denna typ av riskanalyser kommer bli viktigare då mer ”smarta” delar kommer kopplas samman med primärutrustningen. Följande två områden fokuserar projektet på:

1. Utveckling av metoder för investeringsoptimering med avseende på risk, tillförlitlighet, ekonomi och funktion.
2. Hur nya kontrollanläggningar påverkar tillförlitligheten både vad det gäller uppbyggnad och hur standarder utformas.

Detta projekt syftar till att kombinera dessa två koncept, främst med avseende på att hitta en god balans mellan risker och investeringar inom de två områdena (primär och styr/kontroll). Den relevanta frågan blir: Hur mycket smarta och diagnostiska komponenter är optimalt ur ett risk- och tillförlitlighetsperspektiv? Det som initialt kan te sig optimalt, kanske inte är det på lång sikt då tex styrkomponenter kommer behöva bytas ut tidigare än primärutrustningen och dessutom kräva mer kompetens från underhållsorganisationen. Skyddsutrustning, färre avbrott och underhållskostnader måste ställas mot enkla system.

I projektets senare del sker metodutveckling mot optimeringen som syftar till att nå slutmålet, en metod som finner en god balans mellan kostnader och risk där hänsyn tas till en större del av nätet än vad som tidigare gjorts (primär och sekundär utrustning).

Stort tack till programstyrelsen för bra initiativ samt stöd till projektet. Programstyrelsen bestod av följande personer:

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- Hans Andersson, Vattenfall Eldistribution
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- Susanne Olausson, Energiforsk (programansvarig)

Följande bolag har deltagit som intressenter till projektet. Energiforsk framför ett stort tack till samtliga företag för värdefulla insatser.

- Elsäkerhetsverket,
- Ellevio AB,
- Svenska kraftnät,
- Vattenfall Eldistribution AB,
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- Göteborg Energi AB,
- Jämtkraft AB,
- Föreningen Industriell Elteknik, FIE
- Skellefteå Kraft Elnät AB,
- Öresundskraft AB,
- Umeå Energi Elnät AB,
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- Gävle Energi AB,
- Sundsvall Energi Elnät AB,
- AB Borlänge Energi,
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Sammanfattning

Elektriska energisystem är i en transformeringsfas där intelligenta komponenter installeras för att övervaka, kontrollera och hantera elnätet. Att kvantifiera de komplexa konsekvenser på systemets tillförlitlighet som kan uppstå, från integrationen av sådan automatiserad och semi-automatiserad utrustning i det existerande elnätet, är viktigt för underhållsoptimeringen och felhanteringen av nätet. Denna rapport identifierar avancerade metoder inom tillförlitlighetsanalys av energisystem med potentialen att hantera komplexiteten i ett modernt elnät, efter att först ha granskat de traditionella utvärderingsmetoderna.

Effekten på upplevd felfrekvens och dess trend för elnätets lastpunkter, på grund av fel i parallella ledningar i det radiella distributionssystemet, har härletts och modellerats. Exempel på sådan nätstruktur, hämtade från det existerande faktiska elnätet, är analyserade och modellens felfrekvenstrend jämförs med trenden från det verkliga elnätet. Analysen visar att det går att identifiera och mäta den komplexa och dolda felsannolikheten som beror på både oönskad aktivitet av brytare och funktionsfel i skyddssystemet.

De uppmätta sannolikheterna användes till att beräkna skydds- och kontrollutrustningens påverkan på systemets tillförlitlighet. De erhållna resultaten verifierades genom att jämföra dem med elkraftsforskares observationer från tio års felstatistik på skyddssystem.

Summary

Power systems are in a phase of automation where intelligent components and sub-systems are employed to monitor, control and manage the grid. Quantifying the complex consequences on system reliability, from the integration of such automated and semi-automated equipment into the existing grid is important for maintenance optimisation and fault mitigation. This report identifies the advanced approaches in power system reliability analysis with the potential to capture the complications and correlations in modern power grid after reviewing the traditional reliability evaluation methods.

The effect and corresponding trend of additional feeder lines in a radial distribution system on the net interruption rate experienced at load ends of feeders are derived and modelled. Such real-world substation architectures are analysed and the aforementioned trends are compared with those from the practical grid. Thus, the analysis was able to identify and measure the complex hidden failure probabilities due to both unwanted operation of breakers and functional failure of protection systems.

The measured probabilities were used to calculate the impact of protection and control equipment on system reliability. The obtained results were verified by comparing it with the observations by energy researchers on ten years of protection system failure statistics.

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1 Reliability Block Diagram model and theoretical estimation of failure events

Consider the structure of a bus with one incoming and *n* outgoing feeders; following can be possible fault cases in this structure. The assumed possibilities are included in the updated Reliability Block Diagram (RBD) shown in Figure 1.

1. A fault in a conductor is isolated by its corresponding breaker. The repair time for this fault depends on the average repair duration of the failed conductor. This is counted as the active failure of conductor component or grid failures.
2. Faults can occur directly to a feeder line breaker. This again opens the station breaker. The whole system could be out of supply during the repair and restoration of the failed breaker if there are no further provisions to isolate the faulty section. In Figure 3.3 this case is counted as the active failure of feeder breakers. Note that in a radial feeder design as considered here failure of the station breaker affects all lines.
3. Passive faults can occur to feeder breakers due to mal-operation of protection system. Physical failures in feeder line components which simply open the line without causing further faults are also included. So only the faulty feeder will experience outage time.
4. Breaker operation failure due to physical or wrong protection system action in relation to a fault in feeder conductors could potentially disconnect all the feeder lines.
5. The complex sympathetic trips in relation to fault currents in neighbouring sections could escalate at least one additional feeder than the faulty one.

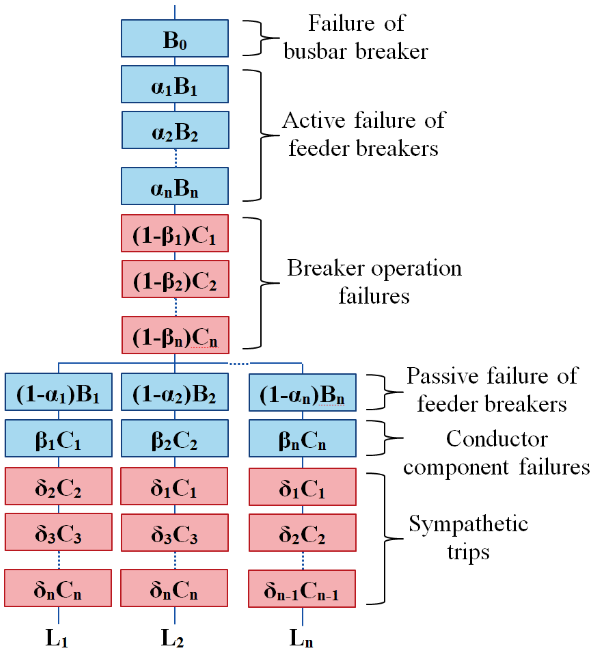

Figure 1: RBD counting in sympathetic and breaker operation failure represented by component blocks and probability indices

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Considering this set of faults to be the only possible set, at the average failure rate experienced at a load end is observed. Blocks marked as B and C represents the effective reliability impact of breakers and conductors respectively. The variables α, β and δ followed by a number to represent the effecting feeder line is used to denote the hidden failure probabilities. Here, α and β are the ratios of active failures to total failures for a breaker and conductor respectively. The term δ represent the frequency of sympathetic faults that can occur overlapping with a failure event in a conductor.

Including the sympathetic tripping and breaker operation failure, the overall failure rate of load point 'L_i' can be as follows:

$$\boldsymbol{\lambda_{L_i} \approx \lambda_{B_0} + (1-\alpha_i)\lambda_{B_i} + \beta_i\lambda_{C_i} + \sum_j[(\alpha_j\lambda_{B_j}) + (1-\beta_j)\lambda_{C_j}] + \sum_{j=1}^{n,j\neq i}\delta_j\lambda_{C_j}} \quad \textbf{(1)}$$

Note that for a fictitious system with only active component faults, the designed model will adopt the values $\alpha i = 1$, $\beta j = 1$ and $\delta j = 0$. The probability of false trips can vary widely in power systems depending of several factors such as design of the grid, presence of modern relays, setting errors, wrong manoeuvres, nature of the components etc.

2 Approach

As the formulation of net failure rate calculations for substation and feeder structures is complete, the approach is to arrive at two models and compare them to arrive at hidden failure probability estimates in practical distribution systems. The RBD method is used for the distinctive calculation of failure rates; that is whether a failure event affects one single feeder section or more. This calculation logic is set up in Matlab and a platform of network design with station, busbar and feeder details is used to calculate overlapping failure event probabilities based on optimization constraints α, β and δ. This constitutes a simulation model.

The performance indices reported by utility for the same network is collected and utilized to structure a model based on the real-world data called as the data model. The data model acts as a fixed platform in the compiled Matlab program to which the simulation model can optimized with curve fitting optimization methods. The program is so designed that the hidden failure probabilities are the optimization constraints. The final values of the constraints for optimal fit can thus represent the practical values of hidden failure probabilities, that is α, β and δ.

3 Model simulation and practical case study

Based on the formula developed, the performance and availability of different substations can be plotted against the number of outgoing feeders from corresponding station. It is to be noted that higher number of feeder lines can imply more number of potential failure scenarios. Due to increased number of relay mal-operations affecting with more number of feeders and feeder protection systems, a consequential variation can be observed while calculating the overall failure rate at all load points. Note that various scenarios are to be considered regarding sympathetic trip probability and breaker grading failure probability. Depending on the quality of erecting, design of the protection system and criticality of connections, some breaker control can be relatively more accurate than others. More detailed description of the considered scenarios is given in the simulation model in the next section.

Comparing real world examples with the modelled structure, more clarity can be attained about the probability of various failure modes described in the previous section. For this, the additional required data for the approach adopted here are performance indices relating substations, feeder system and substation design, number of connected customers, number of secondary substations feeding etc. This data can be used to generate similar plots which contrast the difference in performance of substations as the outgoing feeders with breaker relays subjected to passive and stuck-condition faults. From the trend of the net effective failure rate per load point or System Average Interruption Frequency Index (SAIFI) varying in accordance with the total number of feeder lines from each busbar combined with Equation (1), the practical approximate distribution of α, β and δ can be observed. Further on this is described in the data model in the next section.

A model has been designed to assess the net failure rate experienced at the load end of each feeder lines as in the station and feeder layout shown in Figure 2. In the substation architecture the busbars at both ends are represented as BB1 and BB2 respectively. Two station breakers B01 and B02 on either side of the station transformer T1 is provided. The outgoing feeder structure is similar to the reference branching feeder layout previously modelled. The component failure rates used in the model are assumed from related studies and system reported values.

3.1 SIMULATION MODEL

A model has been designed to assess the net failure rate experienced at the load end of each feeder lines as in the station and feeder layout shown in Figure 2. In the substation architecture the busbars at both ends are represented as BB1 and BB2 respectively. Two station breakers B01 and B02 on either side of the station transformer T1 is provided. The outgoing feeder structure is similar to the reference branching feeder layout previously modelled.

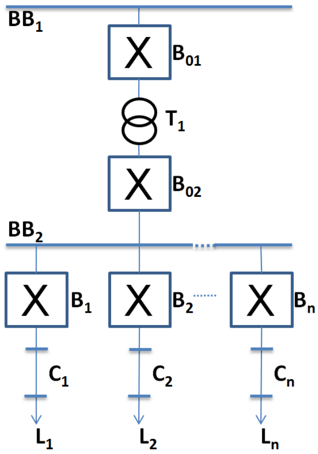

Figure 2: Substation components and outgoing parallel feeders.

Ideally, the presence of parallel feeders is not expected to degrade the performance of another line. But, due to the occurrence of undesired breaker relay trips chiefly due to misinterpreted fault signals and complex logics of relay triggering systems, the former is often not the case. Sympathetic trips which affect lines other than the actual faulty feeders and sensitivity grading overlaps which unwantedly isolate healthy lines along with the faulty ones are clearly present in practical systems today. Combining the layout in Figure 2 with the component data adopted and total feeder length connected to busbars from real world sample data as in Table I, the simulation model can be executed.

Note that in order to estimate the SAIFI for customers connected to each busbar in a station, proper assumptions should be adopted on the number of customers affected by each failure. Not all the additional scenarios considered affect all the customers simultaneously during a failure event. Initially, the variation of SAIFI at busbar level for all the customers supplied through that particular busbar against the number of parallel feeders connected in the physical layout to the busbar is observed. If the system is assumed to comprise only of active component faults, the calculation run can be done keeping $\alpha = 1$, $\beta = 1$ and $\delta = 0$. The linear trend plot of such a case is given in Figure 3.

However, the distribution of active, passive, sympathetic and breaker grading failures affecting the overall system need to be analysed from a practical system. The data for this task is introduced in the next.

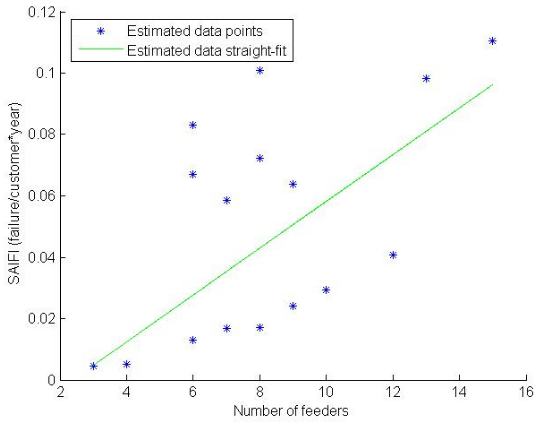

Figure 3: Simulated trend of busbar level SAIFI against number of feeders per busbar for a system with only active component failures.

3.2 DATA MODEL

The data model is based on different parts of the electrical grid in Stockholm municipality, Sweden. Data was collected for different substations of varying size, design, locality and customer distributions. The reliability performance indices for the different substations were investigated. The statistical interruption frequencies observed at the level of each separated busbars in all the stations where combined with the length and number of feeders connected to those busbars. Practical values generally applicable to the reliability of components in the system were also studied.

To have an average representation, stations from different sub-areas were studied. The total municipality area has been further divided into three different sub-areas namely area 1, area 2 and area 3, all of them with their own technical and environmental specifications. For each of the subareas, data for three different substations as well as each of the substation’s distribution grids have been investigated.

Table I consolidated the data so collected which in turn is applied during the modelling. The stations are numbered in Table 4.2 such that area 1 corresponds to first three stations, area 2 corresponds to station 4 to 6 and area 3 correspond to station 7 to 9.

Table 2-1 Substation and Feeder Layout Data.

Substation	Total number of feeders	Station level SAIFI (failure/ customer *year)	Average feeder length per station (km)	Net failure rate for feeder component (failure/year)	Number of separated busbars	Busbar	Number of feeders per busbar	Busbar level SAIFI (failure/ customer *year)
1	43	0.134	1.467	0.02641	4	1	10	0.031163
						2	9	0.028047
						3	12	0.037395
						4	12	0.037395
2	44	0.602	2.047	0.03685	8	5	7	0.095773
						6	7	0.095773
						7	6	0.082091
						8	6	0.082091
						9	3	0.041045
						10	3	0.041045
						11	6	0.082091
						12	6	0.082091
3	48	0.103	1.303	0.02345	8	13	8	0.017167
						14	8	0.017167
						15	4	0.008583
						16	4	0.008583
						17	4	0.008583
						18	4	0.008583
						19	8	0.017167
						20	8	0.017167
4	15	0.271	3.169	0.05704	2	23	7	0.126467
						24	8	0.144533
5	12	0.192	6.062	0.10912	2	25	6	0.096000
						26	6	0.096000
6	18	0.456	2.156	0.03881	2	27	9	0.228000
						28	9	0.228000
7	30	0.418	4.057	0.07303	2	31	15	0.209000
						32	15	0.209000
8	26	0.451	3.796	0.06833	2	33	13	0.225500
						34	13	0.225500
9	14	0.158	5.513	0.09923	2	35	8	0.090286
						36	6	0.067714

4 Analysis and discussion

The model is built on the data presented in Table I and trend of busbar level SAIFI against number of feeders per busbar for the analysed system which potentially include all the consequential failures from all failure modes. This is presented as the trend of the observed data points in Figure 4.

Comparing the two trend lines in Figure 4 strongly suggests that in practical systems, more number of failures affect the load points connected to each busbar represented by the data points than only active mode failures. The trend line fitting from the practical case clearly display poorer SAIFI per data points than the only active failure assumption case. The analysis sets the probabilities of various failure modes as optimisation constraints, so that comparison of the simulation model and data model suggests their approximate distribution in practical systems. It is suggested in background literature on substation failure modes that active faults are more frequent than other cases. Hence practical values of α and β should be closer to one than zero.

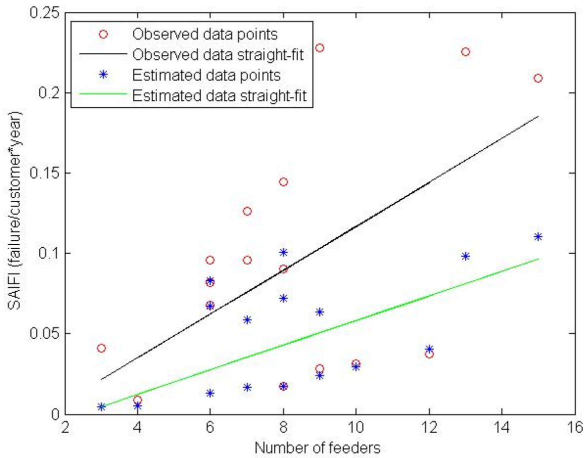

Figure 4: Observed trend of busbar level SAIFI against number of feeders per busbar from the data for the existing system along with the simulated data with only active failures in the system.

Passive and overlapping failure events should be considered as less frequent events and hence (1- α) and δ should be closer to zero than one. Practical combinations of the specific values of constraints hence obtained, suggests the approximate probability range in real-world systems. The curve fitting optimisation suggested α, β and δ to be 0.99, 0.82 and 0.038 respectively. Figure 5 shows the curve fitting trend lines that give the mentioned result.

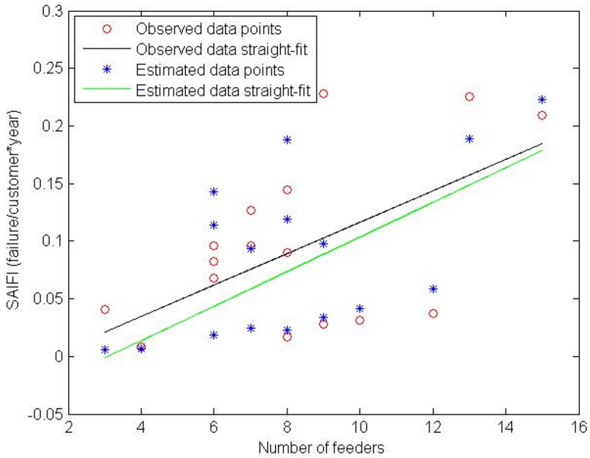

Figure 5: Curve fitting optimisation of estimated trend with the observed data.

The values of constraints arrived through the analysis can be specific to the reference radial branching feeder structure considered here. But the observations lie within a practical range. Another supporting argument can be the effective proportion of protection system involved faults. As per the considerations, there can be 3 categories of faults other than the active component failures: the passive breaker openings, breaker operation failure and sympathetic trips. Extracting the percentage of such cases from the total calculated SAIFI was done.

With the calculations from the substation data (using components and feeder length to calculate failure rate and SAIFI), about 36.63% of the failures associates with protection. In the considered system, when estimation is conducted considering the active failures to be mainly the primary faults and the passive, sympathetic trips and breaker operation failure to be the secondary faults, the distribution lies in the observed range. See Figure 6

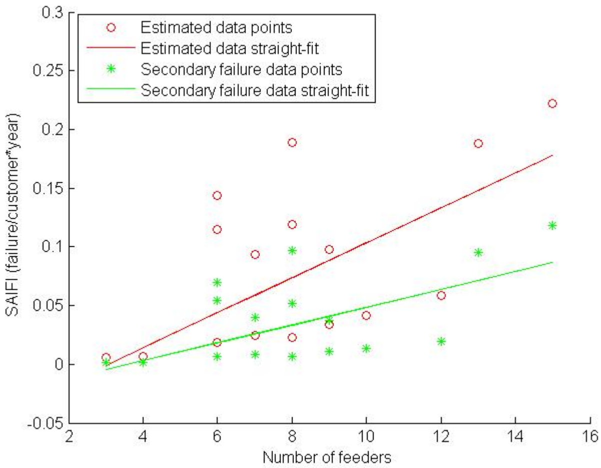

Figure 6: Ratio of estimated total SAIFI and SAIFI due to secondary equipment faults against number of feeders per busbar.

5 Conclusion

This work initially observes the major concerns on reliability evaluation of automated and semi-automated power system architectures. The correlations between different equipment within power system are established and the need to evaluate complex reliability impacts of such networks is identified. Focusing on the modes of failures and false trips occurring in power distribution systems, the question of correlated component reliability is addressed.

A RBD based approach to capture the impact of both active grid component failures and secondary equipment failures separately is introduced. The presence of faults other than active components was initially confirmed. By running an optimisation between a theoretical model and the model from a detailed case study, the approximate distribution was observed. The observation of probabilities of protection and control equipment related failures are justified with the support of statistical observations from distribution systems.

For the observed substation and branching feeder structures at distribution level, about 36.63% of the failures are identified to be not introduced through the active failure of primary grid components. The protection system reliability hence has a critical impact on the performance of the distribution system. With this outcome, the study takes forward the understanding of correlated failure events in power systems. The research is ongoing with extending the model to more generalizable cases along with investigating further on specific failure modes.

6 Reference

Sajeesh Babu, “Reliability Evaluation of Distribution Architectures Considering Failure Modes and Correlated Events”, Licentiate thesis 20151020, Department of Electromagnetic Engineering, School of Electrical Engineering, KTH, Stockholm Sweden.

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