Impact of Manual Versus Automatic Transfer Switching on the Reliability Levels of an Industrial Plant

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***Abstract*—Detailed reliability modeling and analysis of industrial plants provides an estimate of the frequency and duration of load point interruptions. The duration of repair and switching activities necessary to restore a unique power system configuration to a normal operating state from an outage state has a significant impact on the power system reliability levels of industrial power systems. This paper presents and discusses the significant variations in the frequency and duration of load point interruptions at an industrial plant due to manual and automatic switching activities. Three case studies with different percentages of open- and short-circuit failure modes of circuit breakers and fuses will also be presented and discussed for both manual and automatic switching restoration activities.**

***Index Terms*—Automatic, industrial plant, manual, reliability, switching, transfer.**

I. INTRODUCTION

IN any industrial plant a very high degree of reliability is required. The complexity of the modern power systems, the dependence of society upon them, and the large investment costs required has lead to quantitative reliability analysis of power systems. Quantitative evaluation and design of reliable electrical industrial power systems is important due to the high costs associated with power equipment outages and curtailed industrial processes. In this paper the Zone Branch methodology [1] is used for reliability evaluation. The methodology can readily be used to evaluate the impact of restoration and switching activities and the impact of the failure of protection schemes at individual load points.

A Zone Branch single-line diagram is drawn from a single-line schematic of an industrial plant. The reliability evaluation is carried out for each load point using the direct path Zone Branch method [1]. For this paper the equipment reliability data were obtained from IEEE Standards 493–1997 (i.e., IEEE Gold Book) [2].

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II. SUMMARY OF ZONE BRANCH CONCEPTS

The basic element in graphical or digital representation of an industrial power system feeder circuit is a link, i.e., a homogeneous connection between any two nodes or buses in a power system configuration. A link may be a piece of electrical equipment connecting two points in the circuit such as transformer or regulator, or a length of overhead line or cable composed of the same material over its entire length.

Protective equipment is normally installed at the beginning of a link or branch or feeder section in order to protect proceeding equipment from faults within that link or branch or feeder section. Some of the basic protective equipment used in industrial power distribution systems are fuses, reclosers, sectionalizers, breakers and relays, and automatic and manual isolating or disconnecting switches [2], [7], [9].

In order to evaluate the protection coordination and reliability characteristics of a given circuit, it is necessary to divide a circuit into protective zones. Essentially, a protective zone is a part of an industrial distribution feeder circuit that can isolate or detach itself automatically or manually from the remaining circuit if a permanent fault occurs in any of its links. Evaluation of protection equipment characteristics establishes whether the protective equipment can isolate faults in the branches of the affected circuit from the remaining circuit. The speed of isolation will dictate whether any "sensitive" equipment on the remaining circuit will be interrupted, a critical consideration for 24-hour 7-day-a-week power system operation.

The concept of protective zone branches will initially be based upon the following assumptions.

1) All faults are permanent faults.
2) The protective equipment perfectly isolates all permanent faults instantaneously.
3) The protective equipment is perfectly coordinated, i.e., the device closest to the fault operates first.
4) The protective equipment does not fail.

Generally, each industrial feeder circuit is connected to a source of normal supply, which has protective equipment to isolate feeder faults from the remainder of the system.

The first step in defining the first zone is to identify all branches, transformers and related equipment in which a permanent fault of this equipment would resulting only the normal

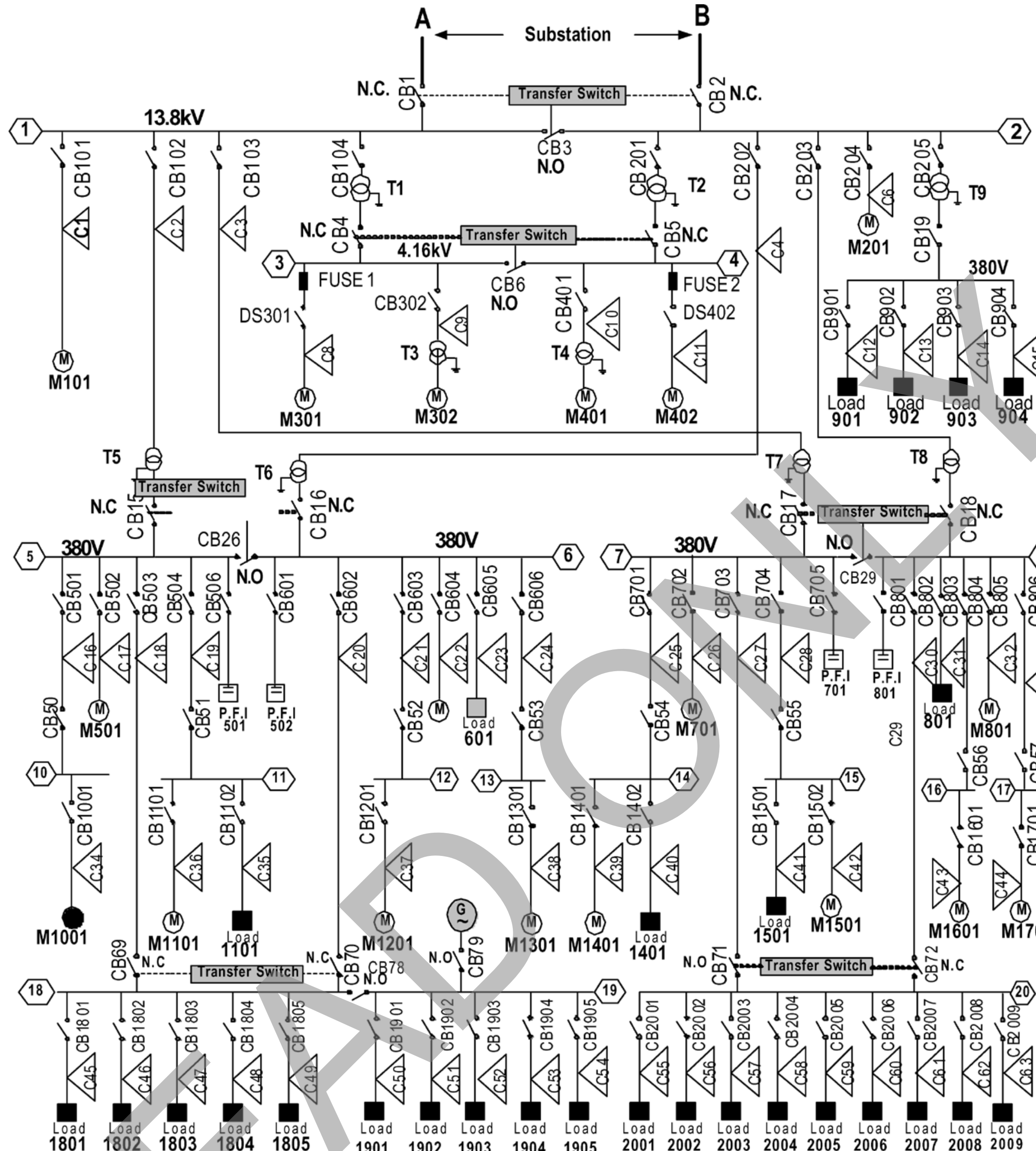

Fig. 1. Single-line diagram of industrial plant.

supply protective equipment recognizing and isolating the permanent fault. These branches, transformer, etc., are labeled as zone-1 equipment. They are generally unprotected branch lines or feeder sections and transformers connected radially to the power source or main of the feeder circuit.

The second step in identifying protective zones is to identify permanent faults in links, which would result in some protective device, other than the normal supply, isolating the fault of the link with its connection with the zone-1 link. These links are labeled as zone-2 branch i, where "i" is the branch number. The zone number represents the number of protective components between the source and the individual links that sense the fault. The procedure of classifying links into their respective zones is continued until all the links have been labeled.

The symbol $\lambda(i,j)$ is the failure rate of zone i, branch j. Associated with each zone branch is an isolating device labeled $S(i,j)$, where "i" is the zone number and "j" is the branch number. These isolating devices can be manual or automatic switches, fuses, reclosers, sectionalizers, relay breaker combinations, etc.

The failure rate $\lambda(i,j)$ of any zone i, branch j is the sum of all the equipment failure rates whose failure will result in only the operation of the isolating device of zone i, branch j.

It can be shown that the total failure rate, i.e., $\lambda T(i,j)$ and the annual downtime, i.e., $\lambda r(i,j)$ for any zone i, branch j is [1]

$$\lambda T(i,j) = \lambda s + \sum RIA(z,k) \times FZB(k)\ \frac{\text{failures}}{\text{year}} \quad (1)$$

$$\lambda r(i,j) = \lambda srs + \sum RIA(z,k) \times FZB(k) \times R(z,k)\ \frac{\text{hours}}{\text{year}} \quad (2)$$

where

λs failure rate of utility supply or plant supply;

rs restoration duration of utility supply;

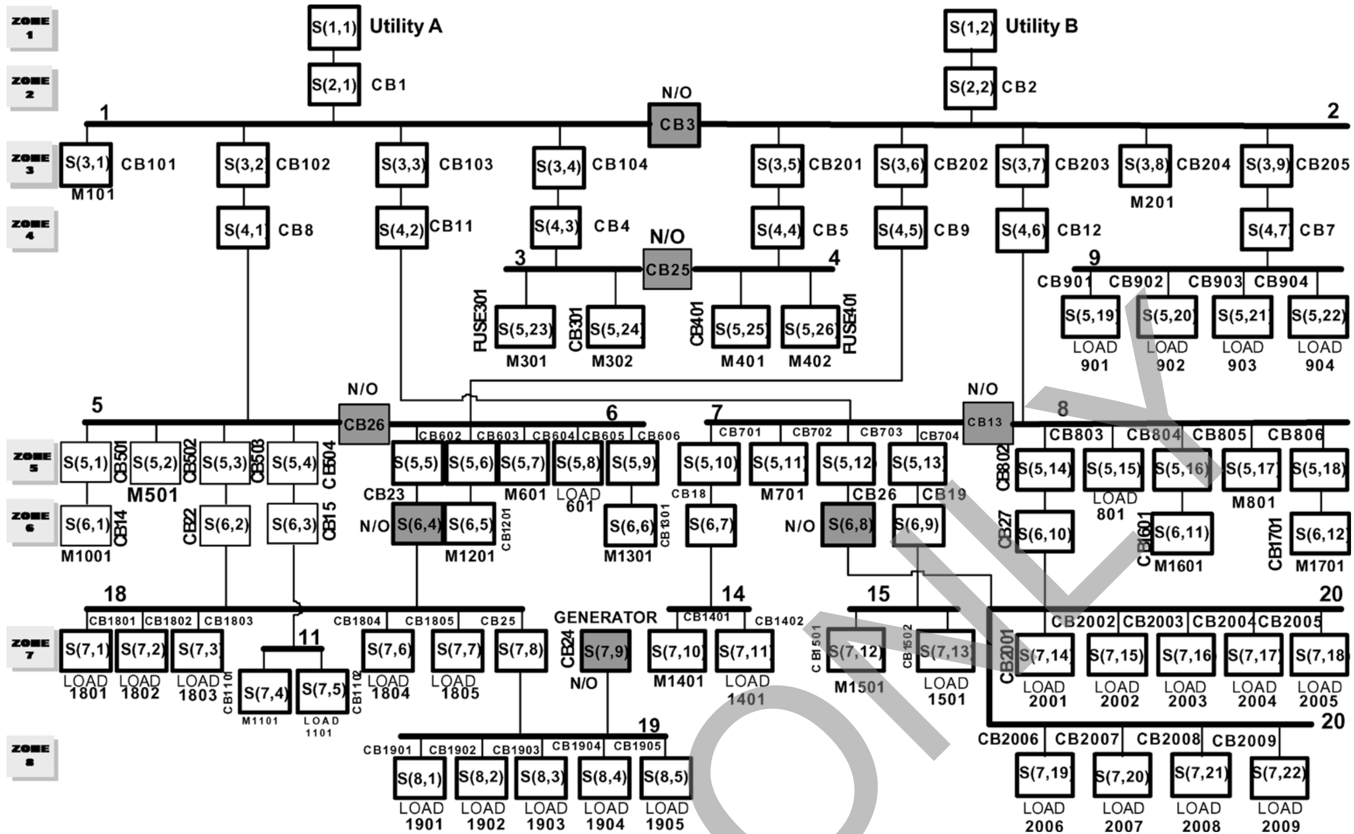

Fig. 2. Zone branch diagram of industrial plant.

z	zone-branch number;
k	total number of zone branches in system;
$R(z,k)$	repair or switching time of zone branch;
$FZB(k)$	failed zone branch array that contains the failure rate of each zone branch k;
$RIA(z,k)$	recognition and isolation array coefficients [1].

In general, the total failure rate $\lambda T(i,j)$ of any zone i branch j is equal to the sum of:

1) failure rate of the power supply or source λs;
2) failure rate of zone i, branch j;
3) sum of the failure rates of any zone branches with lower zone numbers in the direct path from the power source to zone i branch j.

The total failure rate of any zone branch is dependent upon the failure rates of all zone branches in the industrial power system and the probability of isolation devices detecting the permanent fault within their respective zone branch.

III. Direct Path Zone-Branch Method [1]

Direct Path Zone-Branch method is a very effective method for determining the reliability levels of different load points in the large industrial distribution system. A direct path of a zone branch consists of all zone branches (lower zone number) connected in series linking the power source to that particular zone branch. Any zone branch in the direct path to a particular zone branch requires repair activities while those zone branches off the "herringbone" configuration require only switching and isolation duration activities. In this paper the "Direct Path Zone-Branch" method will be used to evaluate reliability indexes at various load points in an industrial plant.

TABLE I
Reliability Data for Power Supplies and Generators

Equipment	Failure Rate (failures/year)	Average Downtime per Failure (hours/failure)
Single 13.8kV Power Supply A	3.6210	2.080
Single 13.8kV Power Supply B	3.6210	2.080
Standby Generator (diesel engine)	0.0670	133.000

IV. Industrial Plant Reliability Data

The industrial plant single line diagram is shown in Fig. 1. The zone branch single-line diagram was drawn from the single-line diagram of the plant and is shown in Fig. 2. The following reliability indexes are calculated for each load point of the industrial plant:

1) frequency of interruptions per year at each load point;
2) Annual interruption duration (λr) expressed in hours per year at each load point.

Given the frequency and annual duration of load point interruptions the average duration per interruption (r) and the reliability (R) can be calculated for each load point. The reliability data for the industrial power system electrical equipment is shown in Tables I–VIII.

TABLE II
RELIABILITY DATA FOR CIRCUIT BREAKERS

Equipment	Failure Rate (failures/year)	Average Downtime per Failure (hours/failure)
Auto Circuit Breaker 13.8kV	0.0064	97.000
Metalclad drawout CB 600V(indoor)	0.0099	9.000
Disconnect Switch 13.8kV(encl)	0.0061	2.800
Disconnect Switch 600V(encl)	0.0061	2.800

TABLE III
RELIABILITY DATA FOR FUSES

Equipment	Failure Rate (failures/year)	Average Downtime per Failure (hours/failure)
Fuse 13.8kV	0.0019	2
Fuse 600V	0.0019	2

TABLE IV
RELIABILITY DATA FOR SWITCHGEAR BUSES

Equipment	Failure Rate (failures/year)	Average Downtime per Failure (hours/failure)
Switchgear Bus per CB(13.8kV)	0.00058	42
Switchgear Bus per CB(600V)	0.00034	24

TABLE V
RELIABILITY DATA FOR CABLES AND CABLE TERMINATIONS

Equipment	Failure Rate (failures/year)	Average Downtime per Failure (hours/failure)
Cable 13.8kV Below Ground (1000ft)	0.0062	35
Cable 0-600V Above Ground (1000ft)	0.0014	10.5
Cable termination (13.8kV)	0.000879	11.1
Cable termination (600V)	0.000127	4

TABLE VI
RELIABILITY DATA FOR TRANSFORMERS

Equipment	Failure Rate (failures/year)	Average Downtime per Failure (hours/failure)
T1 (13.8kV / 600V)	0.0035	48.5
T2 (13.8kV / 600V)	0.0025	64

TABLE VII
SWITCHING TIME DATA

Equipment	Switching Time	Unit
Rsw (Tie-Switch, 13.8kV)	0.25	hour
Auto Transfer Switch (Generator)	300 or 600	second

The "dead" time before the auto switch time was considered is shown in Table VII and it was not considered an outage. R_{sw} (i.e., manual transfer time) was fixed at 15 min.

Most cable lengths were assumed to be 100 ft in Table VIII for the simplicity of longhand calculations and verification. In reality, each cable length would have a unique length.

V. LOAD POINT RELIABILITY INDEXES

Representative samples of load point reliability indexes are shown in Tables IX–XI for manual and automatic switching restoration procedures during industrial plant outages for different breaker failure modes [i.e., open circuit (O/C) and short circuit (S/C].

TABLE VIII
RELIABILITY DATA FOR CABLES

Cable Number	From	To	Length (kft)
C1	BUS1	M101	0.5
C2	BUS1	T5	1
C3	BUS1	T7	1
C4	BUS2	T6	1
C5	BUS2	T8	1
C6	BUS2	M201	0.5
C7	BUS2	T9	0.5
C8	BUS3	M301	0.1
C9	BUS3	M302	0.1
C10	BUS4	M401	0.1
C11	BUS4	M402	0.1
C12	BUS9	LOAD901	0.1
C13	BUS9	LOAD902	0.1
C14	BUS9	LOAD903	0.1
C15	BUS9	LOAD904	0.1
C16	BUS5	BUS10	0.1
C17	BUS5	M501	0.1
C18	BUS5	BUS18	0.1
C19	BUS5	BUS11	0.1
C20	BUS5	PFI501	0.1
C21	BUS5	PFI502	0.1
C22	BUS5	BUS11	0.1
C23	BUS6	BUS12	0.1
C24	BUS6	M601	0.1
C25	BUS6	LOAD601	0.1
C26	BUS6	BUS13	0.1
C27	BUS7	BUS14	0.1
C28	BUS7	M701	0.1
C29	BUS7	BUS20	0.1
C30	BUS7	BUS15	0.1
C31	BUS7	PFI701	0.1
C32	BUS8	PFI801	0.1
C32	BUS8	PFI801	0.1
C33	BUS8	BUS20	0.1
C34	BUS8	LOAD801	0.1
C35	BUS8	BUS16	0.1
C36	BUS8	M801	0.1
C37	BUS8	BUS17	0.1
C38	BUS10	M1001	0.1
C39	BUS11	LOAD1101	0.1
C40	BUS11	M1101	0.1
C41	BUS12	M1201	0.1
C42	BUS13	M1301	0.1
C43	BUS14	M1401	0.1
C44	BUS14	LOAD1401	0.1
C45	BUS15	LOAD1501	0.1
C46	BUS15	M1501	0.1
C47	BUS16	M1601	0.1
C48	BUS17	M1701	0.1
C49	BUS18	LOAD1801	0.1
C50	BUS18	LOAD1802	0.1
C51	BUS18	LOAD1803	0.1
C52	BUS18	LOAD1804	0.1
C53	BUS18	LOAD1805	0.1
C54	BUS19	LOAD1901	0.1
C55	BUS19	LOAD1902	0.1
C56	BUS19	LOAD1903	0.1
C57	BUS19	LOAD1904	0.1
C58	BUS19	LOAD1905	0.1
C59	BUS20	LOAD2001	0.1
C60	BUS20	LOAD2002	0.1
C61	BUS20	LOAD2003	0.1
C62	BUS20	LOAD2004	0.1
C63	BUS20	LOAD2005	0.1
C64	BUS20	LOAD2006	0.1

With reference to these tables the frequency of interruptions at the industrial plant's load points are significantly lower when automatic switching restoration procedures are used during

TABLE IX
LOAD POINT RELIABILITY INDEXES (BREAKER FAILURE MODE: 100% O/C, 0% SC)

	MANUAL SWITCHING		AUTOMATIC SWITCHING	
Load Point	**Frequency of Interruptions** (interruptions / year)	**Annual Interruption Duration** (hours per year)	**Frequency of Interruptions** (interruptions / year)	**ANNUAL INTRRUPTION DURATION** (hours per year)
M101	3.681079	6.083507	0.060079	5.178257
M201	3.681659	6.107867	0.060659	5.202617
M301	3.701019	4.772567	0.060819	3.862517
M302	3.686319	2.375907	0.046119	1.465857
M401	3.686899	2.376052	0.046119	1.465857
M402	3.701599	4.772712	0.060819	3.862517
Load 901	3.667278	2.811244	0.022519	1.905994
M501	3.674706	1.348282	0.033007	0.437857
M1001	3.696205	1.554029	0.054506	0.643604
M1101	3.695793	1.562189	0.054094	0.651764
M1201	3.697125	1.562334	0.054846	0.651764
Load 1401	3.684893	1.362719	0.021087	0.452294
Load 1501	3.684893	1.362719	0.021087	0.452294
M1601	3.697125	1.562334	0.054846	0.651764
Load 1801	3.686253	1.395359	0.022447	0.484934
Load 1901	3.698193	0.544727	0.034387	0.239410
Load 2001	3.688193	1.187208	0.023467	0.271027

TABLE X
LOAD POINT RELIABILITY INDEXES (BREAKER FAILURE MODE: 50% O/C, 50% SC)

	MANUAL SWITCHING		AUTOMATIC SWITCHING	
Load Point	**Frequency of Interruptions** (interruptions / year)	**Annual Interruption Duration** (hours per year)	**Frequency of Interruptions** (interruptions / year)	**ANNUAL INTRRUPTION DURATION** (hours per year)
M101	3.690679	6.705107	0.066479	5.799057
M201	3.694459	7.039867	0.070259	6.133817
M301	3.715569	4.776204	0.060819	3.862517
M302	3.698619	2.071044	0.043869	1.157357
M401	3.702399	2.071989	0.043869	1.157357
M402	3.719349	4.777149	0.060819	3.862517
Load 901	3.693178	4.142744	0.032419	3.236694
M501	3.704106	1.485569	0.047857	0.571507
M1001	3.725605	1.691316	0.069356	0.777254
M1101	3.730143	1.744026	0.073894	0.829964
M1201	3.734675	1.744971	0.074646	0.829964
Load 1401	3.719243	1.544556	0.021087	0.630494
Load 1501	3.719243	1.544556	0.021087	0.630494
M1601	3.734675	1.744971	0.074646	0.829964
Load 1801	3.740403	1.755396	0.042247	0.841334
Load 1901	3.772143	0.683302	0.073987	0.375123
Load 2001	3.765343	1.509683	0.058117	0.582877

plant outages compared with manual switching. With manual switching the frequency of load point interruptions was from 60.7 to 174.7 times higher than the frequency of load point interruptions with automatic switching activities.

The annual load point interruption duration with manual switching procedures ranged from 1.2 to 3.1 times higher than when automatic switching restoration procedures were used.

The frequency of load point interruptions during manual switching restoration procedures varied insignificantly with changes in the percentage of SC and OC breaker failures. However, the frequency of load point interruptions during automatic restoration procedures increased significantly as the percentage of SC breaker failures increased.

The annual duration of load point interruptions during both manual and automatic switching restoration procedures varied significantly with changes in the percentage of SC and OC

TABLE XI
LOAD POINT RELIABILITY INDEXES (BREAKER FAILURE MODE: 0% O/C, 100% SC)

	MANUAL SWITCHING		AUTOMATIC SWITCHING	
Load Point	**Frequency of Interruptions** (interruptions / year)	**Annual Interruption Duration** (hours per year)	**Frequency of Interruptions** (interruptions / year)	**ANNUAL INTRRUPTION DURATION** (hours per year)
M101	3.700279	7.326707	0.072879	6.419857
M201	3.707259	7.971867	0.079859	7.065017
M301	3.730119	4.779842	0.060819	3.862517
M302	3.710919	1.766182	0.041619	0.848857
M401	3.717899	1.767927	0.041619	0.848857
M402	3.737099	4.781587	0.060819	3.862517
Load 901	3.719078	5.474244	0.042319	4.567394
M501	3.733506	1.622857	0.062707	0.705157
M1001	3.755005	1.828604	0.084206	0.910904
M1101	3.764493	1.925864	0.093694	1.008164
M1201	3.772225	1.927609	0.094446	1.008164
Load 1401	3.753593	1.726394	0.021087	0.808694
Load 1501	3.753593	1.726394	0.021087	0.808694
M1601	3.772225	1.927609	0.094446	1.008164
Load 1801	3.794553	2.115434	0.062047	1.197734
Load 1901	3.846093	0.821877	0.113587	0.510835
Load 2001	3.842493	1.832158	0.092767	0.894727

breaker failures. Setting the 100% OC breaker failure mode as a reference, the annual duration of load point interruptions was on average from 1.12 to 1.61 times higher than the 100% OC breaker case study. The dominant failure and outage characteristics for this industrial supply is the high utility feeder frequency and duration of outages which dominates the duration of load point interruptions.

VI. CONCLUSION

This paper has presented and discussed the significant variations in the frequency and duration of load point interruptions at an industrial plant due to manual and automatic switching activities. Three case studies with different percentages of OC and SC failure modes of circuit breakers and fuses were also presented and discussed.

One of the difficulties in assessing reliability analysis of industrial power systems is clearly defining the equipment reliability data, load constraints and assumptions of the reliability models. If the automatic switching procedures are "bumpless" then "sensitive" loads will not be interrupted during the transfer activities. On the other hand, if the automatic switching procedures are too slow and disrupt loads within the industrial power system then the economic advantage of automation is lost.

Many reliability models assume independent component outages which is essentially assuming that all circuit breaker failure modes are 100% OC breaker failures. When SC breaker failures are introduced into the model, then the assumption of independent component outages is violated. The Zone Branch reliability methodology [2], [7], [9], the examples in IEEE Std. 493–1997 (IEEE Gold Book), and [4] readily accommodate dependent component outages in their methodologies.

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