Optimization Technique for Arc Fault Control on the Navy Integrated Power System (IPS)

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***Abstract*—The Navy IPS is a highly complex network that is often times subjected to high-impact contingencies during operations. Cases that result in arc faults, which pose threats to life, mission, and/or ship components, require effective mitigation with minimal manning. This paper is aimed at developing an optimization strategy for quenching arc faults. The approach is based on (a) nonlinear optimization for optimal allocation of remedial control resources, and (b) discrete optimization that incorporates engineering heuristics using an Intelligent System. In the latter case, intelligent decisions are structured into the proposed algorithm to handle discrete control variables. The paper extends the capability of other techniques for solving arc fault control such as Rule Base Systems (RBS). The scheme for improving IPS control and protection against arc fault threats was investigated on a modified Navy IPS.**

***Index Terms*—Arc Faults, Control Coordination, Integrated Power System (IPS), Optimization**

I. INTRODUCTION

Autonomy of control of ship system under all operating conditions is an ever increasing aspect of the Navy. This is partly due to the complex nature of manning a state-of-the-art vessel during normal, alert, or emergency states. As such, an important need to develop and implement modular, intelligent control systems for the integrated system, which consists of a network of fluid/hydraulics, electrical power, and electromechanical systems has been identified.

Aboard the ship, its electric power system is a highly complex network of various generators, backup power, power cables, AC and DC loads, and several converters to transmit power at different voltage levels. Several conditions may develop that give rise to short circuit current flows at a bus or node, within equipment, or on a current-carrying conductor. These are typically high-impact contingencies on the electrical subsystems during operations. The control of a resulting special class of intermittent fault current, termed *arc fault current*, is of special interest to researchers and the power system operators [1]. These arc currents can rapidly degrade the performance of the system, force unwanted shut-down of subsystems, cause fires, and/or cause permanent damage to equipment and devices. As such, isolation and control of the fault with minimal impact on manning, generation schedules, and the ship service loads using available control options aboard the ship is a growing engineering challenge of the Navy. Arc fault, which are also threats to life, mission, and/or components aboard the ship, require effective mitigation with minimal manning.

To date, several methods for handling and interrupting arc faults have been studied [1-5]. They also include the use of Rule Base System (RBS) or Expert Systems (ES), an intelligent system approach. The RBS (or ES) approach has shown promising results for ship service restoration, where the optimal switching to isolate the fault and later to reconfigure the system is desired. It therefore offers an alternative to an integer programming problem. However, RBS suffers from static dimensionality problems and unsuitable as a decision-making support tool in a rapidly changing environment such as on a ship system.

This paper is aimed at developing a coupled optimization strategy for quenching arc faults after they have been detected. The use of RBS as an Intelligent System (IS) application and classical optimization will be investigated in an attempt to solve the arc fault control problem. This involves handling of mixed variables during line switching operations or shunt control. The approach is based on nonlinear optimization for optimal allocation of remedial control resources, and discrete optimization that incorporates engineering heuristics. In the latter case, intelligent decisions can be used to handle discrete control variables. Here, a heuristic-based MIP approach is proposed to solve the discrete problem such as optimal reconfiguration.

The overall implementation strategy involves: (i) establishing power flow feasibility and check radiality and network constraints; Then, computing arc fault currents in the IPS, (ii) solving the nonlinear optimization problem of correcting fault parameters, (iii) solving the discrete problem for correcting parameters relating to the physics of the IPS system (if necessary), and (iv) post-control limits and/or emergency controls and further adjustment of the switching or control sequences to optimize selected objective function(s). The overall scheme for improving the autonomy of IPS control was tested on a modified Navy IPS topology.

Paper Organization: Section II introduces the overall problem and complexity of the required solution, Section III outlines the mathematical modeling and Section IV presents the implementation approach. Section V describes the test system of a reduced Navy IPS. Section VI develops the test

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system data and arc control optimization technique. The discussion and conclusion are presented in subsequent sections of the paper.

II. Introduction

A. Problem Statement

The challenge problem under study is associated with the commonly used model power system topology of the Navy IPS. The complete description can be found in the "ONR Ship Control Challenge Reference Problem", issued by E.L. Zivi, US Naval Academy [3]. Figure 1 shows the general architecture of the Navy IPS.

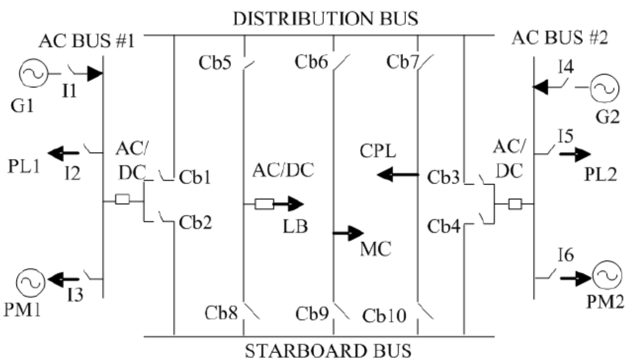

Fig. 1. The Navy Ship Integrated Power System (IPS) Model

The various power machines, converters, and load types are labeled as follows. G: Generator; PL: Pulse Load; PM: Propulsion load or Prime Movers; CPL: Constant Power Load; MC: Motor Loads; AC/DC: Power converter modules that are among the set of Ship Service Converter Modules (SSCM), and Cb: Circuit breakers or switchgears on the distribution lines connected to the main load banks

The following requirements give rise to the complex nature of mitigating arc fault in the IPS:

1. Arc faults detection, not handled in this paper, must correctly and quickly locate the source of the intermittent fault current signatures.
2. Appropriate computation of an arc current depends on the network parameters and the physics of the system [5,10,11].
3. Correcting fault parameters associated with an arc current violation is not a sufficient condition to guarantee global optimization of the limit adjustments.
4. The discrete control problem does not have a closed form solution methodology.
5. Engineering rules that reduced manning requirements for continuity of service and improved system reliability are required in the technical solution approach.

(Section III presents the formulation that addresses 2 to 4 in the proposed algorithm to solve arc fault control.)

B. Complexity of the Mixed Variable Problem

The challenge problem of arc fault control for the Navy IPS is being addressed in this paper using optimization techniques. Specifically, optimal network switching to isolate arc fault with load control involves both discrete and continuous variables since the power flow and balance network conditions must be satisfied. Several research work and applications for mixed integer linear and non-linear problems have been developed [6,8,9]. The general form of this problem is: *Min* $f(x,y)$ *s.t.* $|h(x,y) - h^{max}(x,y)| \leq 0$, $x \in \mathbb{R}$ *and* $y \in \mathbb{Z}$ i.e. x is continuous and y is discrete. For real world situations, these are often times difficult problems to solve due to convexity requirements even after the traditional linearized approximations or LP relaxation on the discrete variables.

However, recent advances in separable programming, new relaxation techniques, and branch and bound techniques have led to better ways of solving the Mixed Integer Program (MIP) with non-linear objectives and/or constraints [6,8].

III. Proposed Mathematical Formulations

A. Parameter Space Identification

The following defines the parameters of the control and state variables of the Navy IPS used for the optimization problem in this paper.

- Vector of control variables ($\mathbf{U_C}$) consisting of generation rescheduling, load shedding, line switching, shunt impedance, and shunt capacitor bank.
- Vector of observable state variables ($\mathbf{X_O}$) consisting of Basic Insulation Level, temperature of generator, transformer winding, transmission line, and converter, and currents of transformer and transmission cables.
- Vector of controllable state variables ($\mathbf{X_C}$) consisting of nodal voltages (for the entire ac-dc system), nodal angles (for the ac sub-system), and generator current.
- 'Arc' vector of controllable state variables ($\mathbf{X_{ARC}}$) consisting of arc current at the faulted bus, arc voltage at the faulted bus, and generator damage factor.

The generator Damage Factor (d_f) is a measure of the generator to withstand a fraction of the impulse current (Ampere.second) resulting from intermittent or sustained arc fault conditions over time without critical damage to its alternator windings.

B. Optimization Problem

The problem takes the general form:

$$Min/Max \;\; \mathrm{F(X,U)} \tag{1}$$

$$\text{s.t.} \quad X_O^{\min} \leq X_O \leq X_O^{\max} \tag{2}$$

$$X_C^{\min} \leq X_C \leq X_C^{\max} \tag{3}$$

$$X_{arc}^{\min} \leq X_{arc} \leq X_{arc}^{\max} \tag{4}$$

$$U^{\min} \leq U \leq U^{\max} \tag{5}$$

Where the function, $\boldsymbol{F}$ represents a multi-objective goal, $\boldsymbol{X}$ represents the vector of state variables, and $\boldsymbol{U}$ represents the vector of control variables of the IPS system.

Also, in some instances of IPS control, it becomes necessary to perform a sequence of line switching to prevent system collapse or permanent damage due to the presence of an arc fault. Here, a primary goal is to achieve optimal load balancing by minimizing the switching operations that would have otherwise reduced the power flow distribution in the network. This is subject to maintaining the integrity of the robust ring structure of a reliable IPS, minimum switching operations, and load flow constraints. The formulation of this problem, which presents itself as a special class of a Nonlinear Mixed Integer Programming (NLMIP), takes this issue into account.

C. Objective Functions Modeling

The following candidate objectives were developed.

1) Maximizing the Ship Service Loads that are not isolated during the fault period

$$F_1(\omega_i, L_i) = Max\left\{k_1 \sum_{i=1}^{NSL} (\omega_i L_i)\right\} \tag{6}$$

Where

ω_i : Priority weighting of the composite service loads
L_i : i^{th} ship service load in the system.
k_1 : Normalizing or cost conversion scaling factor.
NSL : Total number of ship service load banks being served energy.

2) Minimizing the Total Violations in all cables

$$F_2(I_{ij}) = Min\left\{k_2 \sum_{\substack{i,j=1\\(i\neq j)}}^{NL} \left(I_{ij}^{\max} - |I_{ij}|\right)^2\right\} \tag{7}$$

Where

$I_{ij}^{\max}$: Upper limit of the current flow through the ij^{th} cable.
I_{ij} : Actual current flow through the ij^{th} cable that is in violation of its constraint.
k_2 : Normalizing or cost conversion scaling factor.
NL : Total number of ship service load banks being served energy.

3) Minimizing the Total Overload in all cables

The goal is to maximize the NC switches and minimize the NO switches. This can be represented in the form of a purely min/max problem as follows.

$$F_3(x_i) = Max\left\{k_3 \sum_{i=1}^{N_{NC}} \sum_{j=1}^{N_{NO}} \left(\hat{x}_i - \hat{x}_j\right)\right\} \tag{8}$$

Where

$\hat{x}_i$: State of the i^{th} circuit breaker or switch.
N_{NC} : Total number of normally closed switches.
N_{NO} : Total number of normally closed switches.
N_i : State of the i^{th} non-overlapping ring.
k_3 : Normalizing / cost conversion scaling factor.

$\hat{x}_i$ is 1 or 0 denoting on and off positions, respectively. And, N_i is 1 or 0 depending on whether the ring of open or closed by switching. N^{min} is a user-defined minimum number of rings that guarantees a certain set of vital or critical loads is served.

D. Equality Constraints Modeling

These include real and reactive power balances.

1) Real Power Balance to the entire network

This constraint is represented by the real power balance at each bus or the overall power balance of the system. In the latter case, we have

$$\sum_{i=1}^{NG}\left(P_{gi} + P_{gi}^{reserve}\right) - \sum_{k=1}^{NB_{AC}+NB_{DC}}\left(P_{Dk}\right) - P_{Loss} = 0 \tag{9}$$

Assuming the real losses in the AC network is much less than the losses in the DC system, we obtain

$$P_{Loss} \cong \eta_{conv}\left(\sum_{i=1}^{NG} P_{gi}\right) + \sum_{\substack{i,j=1\\(i\neq j)}}^{NL_{DC}}\left(I_{ij}^2 r_{ij}\right) \tag{10}$$

Here, η_{conv} is the average efficiency of all AC-DC converters in the system when operating at the rated power. Therefore, the power balance for the system becomes

$$\sum_{i=1}^{NG}\left\{(1-\eta_{conv})P_{gi} + P_{gi}^{reserve}\right\} - \sum_{k=1}^{NB_{AC}+NB_{DC}}\left(P_{Dk}\right) - \sum_{\substack{i,j=1\\(i\neq j)}}^{NL_{DC}}\left(I_{ij}^2 r_{ij}\right) \cong 0 \tag{11}$$

2) Reactive Power Balance to the entire network

Since the reactive power flow in the DC subsystem is zero, then, the reactive power balance of the system reduces to that of the AC sub-system. Therefore, the corresponding equality constraint is

$$\sum_{i=1}^{NG}\left(Q_{gi} + Q_{gi}^{reserve}\right) - \sum_{k=1}^{NB_{AC}}\left(Q_{Dk}\right) - \sum_{\substack{i,j=1\\(i\neq j)}}^{NL_{AC}}\left(I_{ij}^2 x_{ij}\right) = 0 \tag{12}$$

Equations (5) - (8) and feasibility conditions obtained from solving the AC-DC Load Flow of the IPS system using a Differential Algebraic Equations (DAE)-based method or any other suitable Load Flow technique. This solution will serve as input to the overall system optimizer.

E. Inequality Constraints Modeling

These constraints are represented in three sets that accounts for parameter limits.These are limits on (i) the physical nature of the system, (ii) the electrical network, and (iii) arc parameters. They are summarized as follows.

<u>Limits on the Physical System</u>

Basic Insulation Level,	$0 < BIL \le BIL^{\max}$	(13)
Generator Temperature,	$T_g^{\min} \le T_g \le T_g^{\max}$	(14)
Transformer Winding Temperature,	$T_{TRF}^{\min} \le T_{TRF} \le T_{TRF}^{\max}$	(15)
Transmission Line Temperature,	$T_{XM}^{\min} \le T_{XM} \le T_{XM}^{\max}$	(16)
Converter Temperature,	$T_{conv}^{\min} \le T_{conv} \le T_{conv}^{\max}$	(17)

<u>Limits on Current Flows</u>

Generator Current,	$I_{gi}^{\min} \le I_{gi} \le I_{gi}^{\max}$	(17)
Transformer Current,	$I_{TRF}^{\min} \le I_{TRF} \le I_{TRF}^{\max}$	(18)
Transmission Line Current,	$I_{XM}^{\min} \le I_{XM} \le I_{XM}^{\max}$	(19)
Converter Current,	$I_{conv}^{\min} \le I_{conv} \le I_{conv}^{\max}$	(20)

<u>Limits on Arc Parameters</u>

Arc Current at the faulted bus,	$\left|I_F^{arc}\right| \le I^{\max}$	(21)
Arc Voltage at the faulted bus,	$\left|V_F^{arc}\right| \le V^{\max}$	(22)
Damage Factor,	$\left|d_f\right| \le d_f^{\max}$	(23)

Limits on Switching States

Constraints of the switching states

$$\left[\hat{x}_i \left| i \in \{1, N_{NC}\} \right.\right] \in \{1,0\} \tag{24}$$

$$\left[\hat{x}_j \left| j \in \{1, N_{NO}\} \right.\right] \in \{1,0\} \tag{25}$$

Structural or "Ring-bus" constraints

$$\left(\sum_{k=i}^{N^{rings}} N_k\right) - N^{\min} \geq 0 \tag{26}$$

Where $N^{\min} < N^{rings}$ and N_k is 1 if all NC switches in the kth ring are closed or 0 if at least one NO switch in the same ring is open. The nonlinear equation above can be expanded to

$$\sum_{k=1}^{N^{rings}} \left(\prod_{i=1}^{\substack{No\ of\ switches \\ \text{in } ring\ k}} x_i \right) - N^{\min} \geq 0 \tag{27}$$

If there are no ring buses, then the switching sequence should be aimed at maintaining the radiality of the network.

F. Performance and Severity Indices

For system state, we define a Performance Index, $PI_{\rho Xi}$ of each parameter in the constraint set that is computed as

$$PI_{\rho_{X_i}} = \left| \frac{\rho_{X_i}}{\rho_{X_i}^{\max}} \right| \tag{28}$$

This is used to compute an overall Severity Index, *SI* which is defined as a weighted sum of all the performance indices of the overall system state $X(\rho)=[X_1,X_2,X_3]^T$. Weights ω_i for $\forall i = [1,2,3]$ are used to account for the dominance of a set of parameters on the state X_i such that:

$$SI = \sum_{i=1}^{3} \omega_i \left| \frac{X_i}{X_i^{\max}} \right| = \sum_{i=1}^{3} \sum_{j=1}^{nk_i} \left(\omega_i \left| \frac{\rho_{X_i}(j)}{\rho_{X_i}^{\max}(j)} \right| \right) \tag{29}$$

Here, $X_i(\rho_{X_i}(k)) = \left[\rho_{X_i}(k) \,|\, \forall k \in \{1, nk_i\}\right]$ and nk_i represents the total number of parameters in state X_i. The weights used in this paper were $\omega_1 = 0.25$, $\omega_2 = 0.35$, and $\omega_3 = 0.40$, respectively.

IV. A Hybrid Intelligent System via a Rule-Base System (RBS) for Arc Fault Control

The procedure embeds the used of a RBS strategy to mitigate arc fault and/or discrete control to maintain the integrity of the network. It assumes that the arc fault has been detected and the procedure features (i) determining arc fault currents, (ii) solving the non-linear programming problem for estimating and/or correcting of arc X3 parameters, (iii) using a RBS strategy to solve the discrete problem that updates or correct parameters X1 and X2 (if necessary), and (iv) post-control limits and/or emergency control with final output.

A summary of the proposed implementation steps is as follows:

Step 1. Determine system topology, parameters spaces, and limits / thresholds ranges of all parameters of state and control variables.

Step 2. Solve the pre-fault load flow problem.

Step 3. Detect and locate an arc fault condition and the affected parameter space.

Step 4. Perform fault analysis under fault condition using the DAE-based voltage and current power flow solution as input. Compute the arc fault current using Network-based, Physics-based, or HIF approaches [5].

Step 5. Compute the Severity Index of the arc fault

Step 6. *If* the Severity Index indicates a "soft arc fault" determines by a design threshold, *then*

a. Solve the nonlinear optimization problem with arc quenching control such as a shunt resistor and check the limits of the physical system.

b. *If* all parameters in X1 and X2 are within the normal operating range, *then*, Display "The arc problem is solved". Goto End.

Step 7. *Otherwise,* the Severity Index indicates a "hard arc fault". Determine the priority of the affected loads and post via alarm system.

Step 8. Apply discrete optimization to open and/or close appropriate switches that isolates the fault point at a bus, line, or ship service equipment or load.

Step 9. Check the limits of parameter are state X1 and X2.

a. *If* there are critical temperature violations remaining, *then* apply emergency load shedding or other evasive controls to reduce overheating of equipment.

b. *Otherwise*, display "All limits are not in violation at post-control and arc fault has been resolved".

Step 10. Display / Save final control schedules.

Step 11. End

The next section describes the modified IPS.

V. Description of IPS System and System Limits

In this paper, a reduced IPS model was adopted to demonstrate the capability of the proposed arc control method. Figure 1 shows a reduced equivalent topology of the Navy IPS, in which maintains the interconnections between the AC and DC subsystems via power conversion modules. The main components of this system are the AC power generators, synchronous loads, propulsion loads, and various power converters. The converters are AC/DC Rectifier units, DC/DC converters or Ship Service Converter Module (SSCM) and DC-AC also referred to as the Ship Service Inverter Module (SSIM) [3-5]. Also, the system supports various loads such as motor controllers, and propulsion, pulse, induction motor, constant power loads, and miscellaneous components.

The system is rated at 40 MW, 4,160VAC (3-phase, 60Hz) generating capacity supplied by 2 units and the DC port (or starboard) distribution bus operates at a maximum 1,000VDC. SSCM steps down this voltage from 800VDC to various power levels (440VAC at 60Hz, 440VA at 400Hz, and 500V DC).

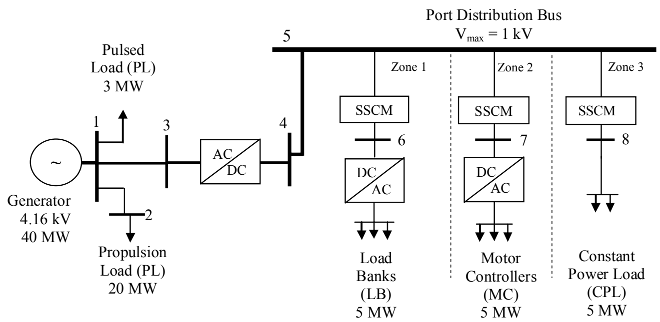

Fig. 2. The Navy Ship Reduced IPS Model

This system is prone critical line flow and voltage limits violations in the event of Single-Line-to-Hull (SLH), Double-Line-to-Hull (DLH), or 3-Phase faults. This situation worsens under arcing conditions, when the peak of the fault current ranges from 57% to 100% of a corresponding bolted fault at the fault location. Also, the voltage drops across the conducting cables with relatively low series impedance results in rapid degradation of the voltage profile in the event of an arc fault to hull. Several control options are embedded in the system, such as line switching done by coordinating the various circuit breakers in the system, to isolate the arc fault. The location of these breakers can be seen in Figure 1.

Selected studies on this system are presented in the next section.

VI. TEST CASE FOR OPTIMAL ARC CONTROL

A. *Description of Cases Studies*

The simulation study was divided as follows:

1. Base case load flow computation using a Differential Algebraic Equation (DAE) based power flow program.
2. Computation of a soft and hard arc faults at selected buses
3. Assessment of fault using the performance and severity measures.
4. Solution to the arc control problem using:
   a. NLP method
   b. Discrete solution technique with engineering rules

First, the study required setting the limits of the constraints presented in Equations (13) to (23).

B. *Limits of the IPS system model under study*

The solution method of the arc control problem described in this paper requires optimal setting of controls and state variables. These variables constitute the system parameter space of the IPS system in terms of (i) the physics of the network, (ii) apparatus limits, and (iii) limits of arc states. Table I shows the parameter space description and typical values of the upper and lower limits used in the optimization problem.

Typical thermal, line flows, and voltage limits for the stability of the ship electric power systems were used and validated using power flow simulations. Other quantities such as the ratings for the Basic Insulation Levels (BIL) were determined using typical rated or base voltage of the cables or system. Other limits such as temperatures of operation were estimated based on standard or name plate specifications for different equipments and apparatus.

TABLE I
PARAMETER OPERATING LIMITS OF IPS COMPONENTS FOR ARCING CONTROL

Description of the Parameters used in IPS Arc Control	Symbol (Units)	Normal Operating Limits
Generator Current	I_g (*p.u.*)	1.10 - 1.25
Generator Temperature	T_g (°C)	40.0 - 135
Generator Power	P_{ij} (*p.u.*)	1.10 - 1.25
Generator Damage Factor	d_f (*Amp.sec*)	$0 < \Delta d_f \leq 0.25 I_{max}$
Transformer Winding Temperature	T_{TRM} (°C)	40.0 - 135
Transformer Current flow	I_{TRM} (*p.u.*)	1.10 - 1.25
Transmission Line Current	I_{XM} (*p.u.*)	0.90 - 1.20
Transmission Line Temperature	T_{XM} (°C)	30.0 - 100
Transmission Line Insulation Level	*BIL* (kV)	70.0 - 80.0
Converter Current	I_{CONV} (*p.u.*)	0.90 - 1.10
Converter Temperature	T_{CONV} (°C)	40.0 - 100

C. *Base Case Load Flow results*

Figure 3 shows the base case power flow results before short circuit or arc fault simulation. All power flows and voltages are within the specified limits in Table I.

The complex impedances of the lines and the reactive power requirements of the AC/DC rectifier units or converters account for the differences in total bus injections and the actual line flows.

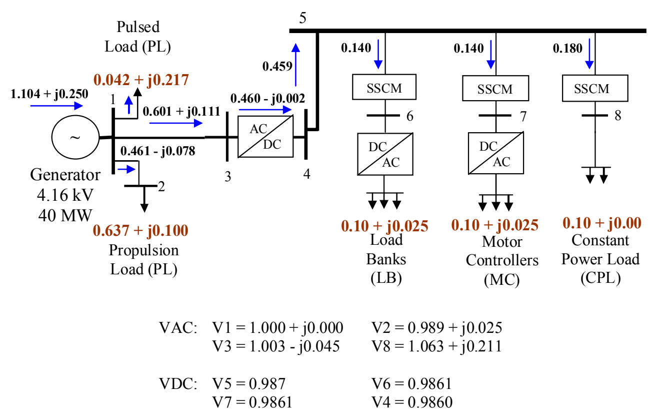

Fig. 3. Base case power flow results

D. *Arc Fault Scenarios*

Using the reduced IPS network, a Single-Line-to-Hull (SLH) was simulated as an arc fault at each bus location in the system. Table II summarizes selected results for faults at buses 3 and 8 that include the violated parameter space. This result shows violations in states X1 and X3 for a fault on bus 3 and violations in state X3 for a fault on bus 8.

TABLE II
CASE STUDIES FOR ARCING FAULT ON THE REDUCED IPS

State Spaces		Fault at Bus 3	Fault at Bus 8
Parameters in groups of states X1, X2, and X3 (as shaded)	Symbol (Units)		
BIL level of the generator	*BIL* (kV)	55.0	54.9
Generator temperature	T_g (°C)	**140**	91
Transformer temperature	T_{TRM} (°C)	**110**	86
Transmission line temperature	T_{XM} (°C)	65	62
Converter temperature	T_{CONV} (°C)	65	62
Generator current	I_g (*p.u.*)	1.025	1.039
Transformer current	I_{TRM} (*p.u.*)	0.923	0.935
Transmission line current	I_{XM} (*p.u.*)	0.43	0.444
Converter current	I_{CONV} (*p.u.*)	0.407	0.421
Phase currents at fault point	I_A (*p.u.*)	**1.368**	**1.194**
	I_B (*p.u.*)	**0.000**	**0.000**
	I_C (*p.u.*)	**0.000**	**0.000**
Phase voltages at fault point	V_A (*p.u.*)	**0.027**	**0.020**
	V_B (*p.u.*)	**0.787**	**0.485**
	V_C (*p.u.*)	**0.397**	**0.485**
Generator Damage factor	d_f *(Amp.sec)*	2.212	2.258

The corresponding severity index was compute using Equation 29 to be 0.58 and 0.56 for the respective arc faults at bus 3 and bus 8, respectively. From this result, we conclude that the arc fault at bus 3 was more severe that at bus 8 and will required stronger or emergency control measures to correct.

E. Optimal Control of Arc Faults at Bus 3 and Bus 8

Since no load shedding or line switching was applied as a control measure in the first instance, it was not necessary to compute the objective function given by Equation 6. Thus, the primary goal is to limit current deviations in the overloaded lines while adjusting the available controls. However, due to the independence of several of the constraints on the objective given in Equation 7, a 2-phase approach is able to solve the problem. Phase 1 involves selection of a candidate set of shunt resistor control using the IS approach such as the RBS for adjustment size and direction followed by computing the new updated power flow. Phase 2 involves checking the objective function using the candidate sets of line currents from the power flow, while the hand-shaking RBS.

In the first iteration of controlling the Single-Line-to-Hull (SLH) fault on Bus 3, the application of the shunt impedance that minimized the arc current was able to remove the hazardous violations of the arc parameters. However, new parameters violation that does not trigger arcing resulted in an overall increase in the severity index from 0.581 to 0.595.

Table III shows the final control options at which stage the arc violations in the dominant parameters were removed.

TABLE III
FINAL CONTROLS FOR REMOVING SLH ARC FAULT AT BUS 3

Controls Used	Adjustment Values in p.u. on the system base	Severity Index (SI)
No control	n/a	0.581
Shunt Control	0.0667 - j0.0004	0.619 (Arc fault was not removed)
Shunt Control	0.5763 - j0.0121	0.595 (Arc Fault was removed but 1 non-arc violation occurred)

For this test case, the performance index of Phase A current in the arc circuit to Hull was 1.368 and 0.192, a significant decrease of 86.0%, after the control was applied.

In another case study, SLH soft arc fault on bus 8, a 0.0667 *p.u.* shunt quenched the network without residual violations.

VII. DISCUSSIONS

This paper discussed a framework for coupling an Intelligent System (IS) technique and classical optimization to solve a complex problem in a typical Navy IPS that involves mixed variables. The investigatory research has been based on studies done using the reduced or simplified Navy IPS. After solving the power flow, radiality and/or ring-bus criteria, and network constraints, the heuristic method is used to check the limits and determine initial controls needed. Further fine-tuning the arc fault control variables (such as shunt resistance for quenching the arc) was aimed at reducing any damage or manning requirement of the IPS.

VIII. CONCLUSIONS

The Navy Ship system is a complex configuration of electrical networks, weapon systems, navigation, life support, etc. We have developed the optimization problem formulation to solve a critical problem - arc faults - that arise in such electrical networks. The proposed approach involves the use of a hybrid of Intelligent Systems and classical optimization to address this problem. The approach suggested is based on nonlinear programming and a formulation for a mixed-integer nonlinear optimization.

The work presented in this paper is adaptable to a more detailed IPS. However, given the complex interactions of the electrical sub-systems of the IPS, full integration of the proposed method requires increased autonomy with decentralized control. Ongoing sponsored research work at the Center for Energy Systems and Control (CESaC) at Howard University is extending these ideas to the fully integrated Navy IPS. At CESaC, we are currently developing Multi-Agent System (MAS) platforms to address this issue and it will take advantage of the approach developed in this paper for supervised arc fault control. The proposed approach with applied IS will be tested for robustness and scalability.

Finally, the application of optimization techniques from the Operation Research community in tackling some of the Navy's power system challenge problems will serve as a benchmark for comparable power systems.

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