A Tutorial on Optical Ground Wire Ratings Analysis for Protection Engineers

Ryan McMaster, P.E.
SCADA and Analytical Services
POWER Engineers, Inc.
Freeport, ME
ryan.mcmaster@powereng.com

Abstract—**Installation of an Optical Ground Wire (OPGW) is an increasingly common upgrade when replacing shield wire(s) on a transmission line, as it provides the added benefit of broadband communications capability. Utilizing such fiber installed inside the shield conductor comes with a substantial risk of damaging the communications circuit from annealing of the shield conductor due to ground fault current flow. The transient current-induced temperature rise on an OPGW is a simple calculation in itself, but sizing of an OPGW for adequate thermal capability requires careful consideration of numerous and often overlooked factors characterizing the total heating energy, many of which fall on the protection engineer to calculate. This paper provides a detailed overview of the principles and process to determine the required thermal withstand capacity of an OPGW and discusses a particularly complex case study with a novel mitigation solution.**

I. INTRODUCTION

An Optical Ground Wire (OPGW), essentially a lightning shield conductor containing one or more fiber optic cables, would seem to present a cost-effective means of adding a broadband communications path to a transmission line that already requires a shield conductor for lightning protection. However, the unique characteristics of OPGW pose additional design constraints over a conventional shield wire. To ensure a reliable installation for critical communication applications such as line teleprotection or Supervisory Control and Data Acquisition (SCADA) systems, an OPGW will likely require additional investments in structural strength and/or the structure grounding systems that offset the cost versus benefit viability of the OPGW, especially in retrofit applications. This paper discusses some of the overall design considerations in applying OPGW to transmission lines. Then, a tutorial is provided for calculating the fault current thermal capacity requirement for an OPGW design application. To ensure a reliable OPGW fiber communications path, the lower specific thermal capacity of OPGW over conventional shield wires needs to be understood and addressed through careful analysis of the protection and grounding design systems.

II. OPGW DESIGN CONSIDERATIONS

OPGW installation design is essentially applying an aerial-supported cable that can satisfy a line's needs for lightning protection and a fiber optic communications path. As with any design, satisfying the needs of the application is a balance of compromises.

As an aerial conductor supported on the line, the OPGW must maintain adequate clearance from phase conductors and objects adjacent to the line. To achieve the needed clearances, the OPGW attachment height can be increased, but doing so increases the length of the lever that the OPGW applies under wind and tension loading. Alternatively, the sag can be reduced by increasing the tension on the OPGW at the dead-end attachment points, but that requires not only stronger dead-end structures, but potentially a larger OPGW for the needed rated breaking strength. Increasing the conductor area also increases the weight and wind burden on the supporting structures.

For the fiber optic application, the number of fiber strands determines the size of the one or more inner fiber bundles within the overall conductor cross-section. As the number of fiber strands increases, either the OPGW overall diameter increases, or the conductor cross-section area decreases relative to that occupied by the fiber.

For lightning protection, the OPGW position at the structure top and the grounding design are key considerations. Increasing the height of the OPGW increases the effectively shielded area for conductors below. However, increasing the height of the OPGW increases the length of the lever and thus the cantilever force it would apply on the supporting structures. Two shield wires may be positioned horizontally to provide the greater shielding area needed for structure configurations with double circuits and/or wide horizontal phase conductor spacing. Two shield wires add burden to the supporting structures, but each shield shares only a portion of the total current flow from a ground fault or residual load current flow due to phase current unbalance. Since the heat generated in the conductor from Ohmic loss is proportional to the square of the current magnitude, splitting the residual current flow among two shield conductors results in a dramatic reduction of losses. The probability of a lightning induced flashover can also be reduced by installing a more extensive structure grounding design or continuous counterpoise system, both of which also reduce the current-carrying duty of the OPGW during a ground fault.

As a grounded conductor, the OPGW is a path for ground fault current and a source of losses from flow of residual current due to phase current unbalance. Reducing the resistance of the conductor portion of the OPGW:

1. reduces the losses from both load unbalance and ground fault current flow;

2. increases overall ground fault current; and
3. increases the portion of total ground fault current that flows back through the OPGW to the source.

Reducing conductor resistance generally requires a larger conductor cross-section or use of more conductive materials. Designing OPGW cross-sections to use higher-conductivity materials like aluminum alloys can offset the reduction of conductor cross-sectional area occupied by the fiber. However, the more conductive materials are generally softer mechanically than the extra-high-strength steel, Alumaweld, or Copperweld materials used for conventional shield wire. As a result, an OPGW compared to a shield wire of equal diameter will typically provide lower specific tension capacity and exhibit greater change in sag as conductor temperature varies. In a retrofit application, it may be necessary to select a larger OPGW than the shield it replaced to provide enough tension capacity to maintain sag within the limits required for electrical clearances.

The OPGW supporting conductor material typically consists of a combination of aluminum and steel alloys to achieve a desired balance in mechanical characteristics. As can be seen in OPGW manufacturers' datasheets, the conductor materials can handle temperatures of 180℃ to 200° C before annealing. Fiber optic strands are typically made of silica glass and can withstand a constant temperature well more than the OPGW's surrounding conductor. Therefore, if the conductor portion of the OPGW assembly is not adequately sized to withstand the ground fault current duty of an application, the conductor may anneal from thermal overload during a fault and mechanically fail the inner fiber optic cable. Also, the concentric placement of the fiber inside the metal supporting conductor does not lend to a practical mid-span splice repair solution, in contrast to a conventional shield wire that can be spliced multiple times in a single span. Repair of a broken OPGW generally requires replacement of an entire span of OPGW to the nearest dead end structures or retrofitting structures into dead ends to support and splice in a new OPGW span at the two dead-end splice points. The consequentially-added two splice points add about 0.6 dB to the fiber communications path losses. This significant disadvantage in repairability emphasizes the importance of accurately calculating the ultimate fault current thermal duty of the OPGW application and satisfying that duty through informed conductor selection, design of supporting structures, and their associated grounding system.

For retrofitting a conventional shield wire with OPGW, a common design approach is to choose an OPGW with the necessary number of fiber strands and an overall assembly with similar sag characteristics, outer diameter, and weight per unit length equal to or less than the existing shield wire. The aim with such an approach is to avoid imposing any greater burden on the supporting structures. Being that the fiber optic material is not an especially effective thermal conductor, an OPGW will generally provide less thermal withstand capacity than a conventional all-metal shield wire of the same diameter. This reduced thermal capacity may not satisfy the fault duty of the application without additional investments in grounding to reduce resistance to ground, segmenting the OPGW into multiple isolated sections, or isolating the OPGW from the substation terminals, all of which make it a less favorable ground source return path and thereby reduce the OPGW fault current duty.

III. OPGW INSTALLATION DESIGN PROCESS

A line construction project generally begins with a transmission planning study identifying the need and specifications for a new or upgraded transmission line, including the required line capacity (in Amperes or Mega-Volt Amperes), number of circuits, and line route. This line upgrade may coincide with the utility's fiber expansion plan, and consequently the project includes scope to add an OPGW with specific fiber count. Then, the transmission line engineering team develops the preliminary physical design of the line, including selection of a candidate OPGW for its fiber count and physical and mechanical characteristics. A utility may have defined standard selections of OPGW to streamline stock materials for repairs and installations.

Prior to completion of the preliminary line design, a protection engineer should calculate the transmission line constants and perform a short circuit study to determine the required thermal rating of the OPGW. To develop an accurate short circuit model of the studied line, a protection engineer needs a complete set of line plan and profile drawings, structure unit drawings, and staking tables. From those references, the phase conductor, OPGW, and shield are identified, as well as the conductor cross-sectional geometry at the structures and at mid-span. Conductor selection and line distance alone satisfy the positive-sequence impedance model. The zero-sequence impedance model, characterized by structure attachment geometry, grounding design, proximity to adjacent lines, and earth resistivity, would have to be modeled approximately; those line design details are generally finalized during the subsequent detailed line design phase. To avoid understating the required thermal capacity of the OPGW, it is important to include a design margin to account for uncertainties in the zero-sequence impedance model. The protection engineer should also select the line protection systems for the application, considering the fault maximum clearing time specified by transmission planning or otherwise follow utility standard design practices. The clearing time of the protection systems will need to be calculated for all fault locations studied, both under normal protection system operation and system contingencies such as a pilot scheme communications channel or relay out of service. Finally, the protection engineer will need to understand the reclosing philosophy established for the line. If the utility has yet to select a preferred terminal for testing the dead line after a fault is cleared, the protection engineer should conservatively assume the end with higher available fault current as the test terminal.

Once an OPGW thermal rating is specified by the protection engineer, an iterative process begins between the transmission line engineer, protection engineer, and possibly grounding and lightning studies engineer to refine the transmission line physical design and satisfy the OPGW thermal rating specification. The solution can be as simple as the transmission line engineer selecting a large enough OPGW to satisfy the entire OPGW thermal rating requirement and augment the supporting structural design to support that OPGW. In cases where an OPGW size is restricted to limit structural impacts, satisfying the thermal rating can involve refining the line grounding, shielding, insulation, and protection system designs to reduce the fault current carrying burden of the OPGW. Discussed in the following sections are the principles and detailed process for performing OPGW thermal ratings analysis and application of mitigation techniques as demonstrated through a real case study.

IV. OPGW THERMAL RATING CALCULATION METHOD

The standard method for calculating the current-temperature relationship of bare overhead conductors is described in IEEE 738-2012 [1]. During steady state pre-fault operation, the grounded OPGW is subject to heating and cooling effects in the form of solar heating, convective cooling (wind), radiant cooling, and ohmic losses from current flow. Assuming that transmission line phase currents are well balanced and that current induced from phase conductors is minimized through design, the steady state current effects on the OPGW temperature can be considered negligible. For a fault transient heating calculation, the solar heating, convective cooling, and radiant cooling effects can be simply accounted for by an assumed pre-fault conductor temperature. A value of 40°C is typical for the basis of the published fault current rating on an OPGW manufacturer datasheet. During a fault, the current heating effects dominates all other effects. Since the fault duration is very short, solar heating, convective cooling, and radiant cooling effects are ignored, and the OPGW heating effect reduces to:

$$T_{Final} = I_{Fault}^{2}\mathrm{t} + T_{Initial} \tag{1}$$

where T is the temperature in Celsius or Kelvin, and t is the fault duration in seconds. On a manufacturer datasheet, the OPGW rated fault current will usually be expressed as a value with units $\mathrm{kA^2s}$, and the assumed initial and final conductor temperatures should be stated.

It is worth noting that lightning transient current flow is not typically considered when determining the design thermal rating of an OPGW. The current magnitude of a lightning strike can approach 250 kA [2], a factor of 625 times the heating energy of a 10-kA fault of identical duration. The duration of a lightning strike, however, is on the order of 0.05 milliseconds [3], whereas a fault detected by instantaneous relay tripping elements and cleared by a three-cycle breaker is expected to clear in 83.33 milliseconds (five cycles), a heating factor 1,666 times that of a lightning strike of equal current magnitude. As a more direct comparison, the heating from a 250-kA lightning strike lasting 0.05 milliseconds is equal to a 6.12-kA fault lasting five-cycles. With typical available transmission line fault currents well above this example figure, OPGW heating from a lightning strike is essentially negligible compared to the heating from a ground fault.

V. OPGW FAULT WITHSTAND ANALYSIS PROCESS

Since the heating of a conductor due to fault current is determined by the fault current magnitude and duration, development of an OPGW thermal rating involves the same tools and techniques used to conduct a system protection study. The OPGW rating analysis simply has a different goal – to determine the worst-case cumulative I^2t heating in a section of OPGW from a fault event, addressing the following considerations, each of which is discussed in more detail:

1. system pre-fault contingencies,
2. the heating contribution of the initial asymmetrical portion of the fault waveform,
3. the actual current flowing through the OPGW,
4. delayed breaker failure clearing,
5. multiple recloses back into the fault, and
6. the time to clear the fault by the protection system.

System Pre-Fault Contingencies – The OPGW fault thermal capacity needs to support faults within the normal system and the system with a single pre-fault contingency. A pre-fault contingency will affect the heating of an OPGW during a fault either by a change in OPGW current flow or fault duration. A pre-fault outage of a line or transformer connected to a remote substation is expected to reduce the remote terminal current contribution (infeed) to a fault on a line, thereby increasing fault current contributed from the local line terminal. Finding the pre-fault outage that increases OPGW current the most usually requires simulating faults and calculating I^2t heating for numerous possible contingencies and fault locations. Documenting the case assumptions, calculation steps, and results in an organized table aids recognition of the controlling cases for the OPGW thermal design specification and for simply demonstrating that analysis was comprehensive. Protection system contingencies such as the loss of a pilot scheme communications system or loss of a protective relay may result in additional fault clearing delay. For a line with redundant pilot schemes, a loss of one pilot scheme or protective relay would pose no impact to fault clearing time. However, if a line has only one pilot scheme among the two protection systems, loss of that pilot scheme would result in delayed clearing of faults beyond the reach of the relay's instantaneous underreaching elements (e.g. Zone 1 ground distance, 50G). The additional heating expected from delayed fault clearing is to some degree offset by the reduced current contribution to a relatively remote fault location, but the delay in fault clearing may prove to be a controlling design case among a comprehensive set of study case calculation results.

Initial Fault Current Asymmetry – The initial asymmetric peak and transient decay of fault current, also referred to as the "DC offset" component of the fault waveform, is one current heating factor that can represent a substantial portion of the total heat energy absorbed by an OPGW during a fault. It is important that the DC offset portion of the fault current is accounted for in the OPGW heating calculations, and yet software tailored for protection coordination studies typically reports only the symmetrical portion of fault currents and no direct measure of the DC offset portion of the current waveform. However, using the symmetrical magnitude of fault current and the X/R ratio reported from the compute model simulation, we can determine the additional heating of the asymmetrical waveform by calculating its RMS value over the fault duration [4]:

$$I_{RMSAsym} = \frac{1}{t_{stop}} \int_0^{t_{stop}} [I_{Pk} \sin(\omega t + \theta - \varphi) - \sin(\theta - \varphi)\, e^{-1\alpha t})]^2 dt \quad (2)$$

where,

t_{stop} is the fault duration in seconds
$\omega = f * 2\pi; f = 60\ Hz$
$\theta = 90° - tan^{-1}\frac{X}{R}$ voltage phase angle at fault onset
$\varphi = tan^{-1}\frac{X}{R}$ difference in angle of fault current with respect to voltage
$a = \frac{\omega}{XR}$ exponential decay time constant
$I_{Pk} = I_{RMSSym}\sqrt{2}$ theoretical maximum peak asymmetrical current

This RMS value can be thought of as a symmetrical equivalent current magnitude accounting for the total heating of the true asymmetrical waveform and should be used as the current magnitude for the OPGW I^2t heating calculations.

OPGW Current Split – For lines with a single OPGW and no other shield wire or continuous counterpoise conductor, the total branch current returning from a fault to a terminal may be a suitably accurate measurement of the current flowing through the OPGW. However, if a line has a second shield or continuous counterpoise system, the fault current will split among the conductor paths according to their impedances [5]. For configurations with unequal OPGW, conventional shield, and/or continuous counterpoise conductor impedances, an accurate measurement of the current split can be obtained by modeling the system and line in a different system analysis program, such as one used for studying electrical system transients, which would allow for more granular component modeling and measurements than typical short circuit modeling software designed specifically for protective relaying studies. One should also consider whether the line constants mathematical model used by the system modeling software accounts for structure grounding either as discrete or distributed components. Each ground is an alternate path for fault current to flow to earth, effectively reducing the total current duty of the OPGW. Not all short circuit simulation programs account for structure grounds, and an engineer performing an OPGW thermal rating study should recognize any such limitations and consider re-modeling the system in another program.

Delayed Breaker Failure Clearing – Delayed clearing of a fault due to a breaker failure is a possible outcome that should be supported by an OPGW thermal rating design. A failed breaker is generally considered in addition to a pre-fault contingency, rather than in lieu of it. A utility should consider whether the OPGW's thermal capacity needs to withstand breaker failure clearing on the last shot of an N-shot reclose sequence, i.e. after N-1 successive faults cleared normally, or whether failed breaker clearing will only be supported on the first and only shot of a fault event. Failed breaker clearing at the end of a multiple-shot reclose sequence may be considered a low enough probability that a utility does not want to size the OPGW to support it. Rather, a utility may choose to support either 1) a sequence of faults cleared normally and unsuccessful reclose attempts to eventual lockout, or 2) only a single fault with delayed breaker failure clearing. Calculation of the total OPGW heating due to a fault cleared by a breaker failure scheme can be considered as two separate fault simulations added together, i.e. the initial fault until the remote end is cleared normally, and then the fault fed only through the local stuck breaker terminal until the time when it is cleared by the breaker failure protection scheme. For a networked system, the OPGW current sourced through the local stuck breaker terminal is generally expected to increase after the remote terminal is cleared via its normal line protection system.

Reclosing Effects – As a practical matter, any cooling of the OPGW during a typical reclose open interval of 15 seconds or less can be ignored due to the limited reduction in temperature expected in such a short time frame. Also, the rate of cooling is only especially sensitive to wind speed, which is highly variable in nature. To demonstrate, an iterative calculation of temperature change due to a current transient was performed for a 795 ACSR "Drake" conductor based on the method defined in section 4.6.3 of IEEE 738-2012. Simulation results are provided in Table 1. The base simulation case is a post-transient ambient temperature of 40°C, no wind, solar exposure at a position latitude of 43°N on August 1st, and enough pre-transient current to result in a steady state current temperature 200°C.

TABLE I. IEEE 738-2012 CALCULATION OF CONDUCTOR TEMPERATURE VERUS TIME AFTER A CURRENT TRANSIENT

Case Description	**Temperature After 15 Seconds**	**Temperature After 10 min.**
Base Case	197.1 °C	130.1 °C
Base Case with Wind Speed 22.35 m/s (50 mph)	176.4 °C	42 °C
Base Case with 0 °C Ambient Temp.	196.8 °C	113.7 °C

The calculation results indicate limited cooling potential during a typical reclose open interval. Without wind, the conductor will require on the order of 60 minutes to return to ambient temperature. Therefore, the total heating duty of an OPGW due to fault current flow should be approximately equal to the heating accumulated from one fault event multiplied by the number of reclose attempts that the line terminal is designed to make.

Fault Clearing Time – To optimally specify an OPGW's thermal capacity, a protection engineer should provide accurate fault clearing times as the fault location varies along the line based on the actual protection design and relay set points. Accurate calculation of the clearing time requires careful consideration of the make and model of relay(s) protecting the line, their protection element setpoints, details of any pilot schemes employed, whether any auxiliary tripping relays are employed, the line terminal breaker(s) interrupting speed(s), and details of any breaker failure protection systems.

VI. CASE STUDY

As a demonstration of the technical principles and analysis approach to determining the required thermal capacity of an OPGW application, a real-world case study is presented.

Described herein is an analysis to determine the fault carrying capacity of a proposed OPGW retrofit for a 2.7-mile 115-kV transmission line connecting stations generically named Station A and Station B. The existing towers were configured to carry a single 3#6 Copperweld shield wire. The OPGW proposed by the transmission line engineering team were sized for the required number of fiber strands and for an overall diameter and weight per lineal foot matching as close to the original shield wire as possible to minimize impact to the structural design. The key design factors considered in the study are as follows:

1. **OPGW Thermal Rating** – 109.0 kA^{2}s (40°C initial temp, 200°C final temp
2. **Line Protection Design -** dual pilot schemes (POTT and DCB); slowest normal clearing is less than five cycles for a solid ground fault anywhere on the line, including the two-cycle breaker interrupting time.
3. **Breaker Failure Fault Clearing Time** – 15 cycles
4. **Reclosing Philosophy -** one shot taken from one terminal on dead 115-kV line
5. **Fault Current Growth Factor** – The utility specified a 10% fault current design margin to address future fault current growth.

The utility's protection group provided their short circuit computer model of the existing system, and with it the subject line constants model was updated according to the revised phase conductors, structure geometry, and initial OPGW selection from the transmission line design. The line constants model's soil resistivity parameter was also verified from measurements at several locations near the line and substations that were taken for related project work.

From the updated short circuit model, initial simulations of ground faults along the line under system normal state and with both end terminals yielded total fault current ranging from 30.7 kA to 41.2 kA. Station A contributed currents from 9.2 kA to 30.0 kA depending on distance to fault, and Station B contributed 5.1 kA to 24.2 kA. Since the line protection design features dual pilot schemes with insignificant difference in clearing time between the two systems, contingency analysis did not need to consider a protection system contingency. Each of the substations is networked with eight to ten other lines, and several of the lines share right-of-way with the subject line. Therefore, the search for controlling design cases under contingency was done by batch simulations of ground faults along the line with both end terminals closed and a single contingency per simulation case of either an infeed line being isolated or a mutually-coupled line being isolated and grounded at both ends. Under contingency, the highest fault current contributed by a terminal was 30.6 kA ∠79° for a close-in fault at Station A with outage of the strongest line infeed connected to the remote end Station B. The short circuit analysis also gathered the highest through currents under contingency for faults at other points on the line. This data was ultimately not a factor defining the basis for the OPGW sizing, since the line was short and the reduction in heating for a fault closer to the middle of the line was not enough for the utility to justify installing multiple sizes of OPGW according to the thermal fault current duty of a particular section of line.

From the highest fault current simulation result of 30.6 kA ∠79°, the X/R ratio was calculated to be $\tan 79° = 5.14$. From (2), the RMS value of asymmetric current with X/R = 5.14 and fault duration of five cycles is 1.078 times symmetrical current, or 33.0 kA. The thermal duty can then be calculated for a worst-case bolted ground fault cleared normally by the line protection:

$$I_{Fault}^2 \mathrm{t} = (33.0\ \mathrm{kA})^2\left({}^{5}/_{60}\ s\right) = 90.8\ \mathrm{kA}^2\mathrm{s} \qquad (3)$$

After this initial fault is cleared, the line reclosing scheme would attempt to restore the line from one terminal. One needs to account for the additional heating event after the terminal recloses back into the fault. For these thermal duty calculations, reclosing is assumed to be attempted from the terminal with the stronger source behind it. A simulation of a close-in fault at Station A with the Station B end opened and the same contingency used for the initial fault case yields a fault current through Station A of 30.7 kA ∠79°, a small increase from the initial fault fed from both terminals. Since the fault current angle relative to positive sequence voltage is identical to the initial fault case, we know that the RMS value of the asymmetric current is $1.078(30.7\ \mathrm{kA}) = 33.1\ \mathrm{kA}$. This fault current cleared again normally in no more than five cycles yields an additional heating duty of $I_{Fault}^2 \mathrm{t} = (33.1\ \mathrm{kA})^2\left({}^{5}/_{60}\ s\right) = 91.3\ \mathrm{kA}^2\mathrm{s}$. Since the reclosing scheme for this line is designed to make only one reclosing attempt, the total OPGW fault thermal withstand duty from a permanent fault cleared twice normally by the line protection is $90.8\ \mathrm{kA}^2\mathrm{s} + 91.3\ \mathrm{kA}^2\mathrm{s} = 182.1\ \mathrm{kA}^2\mathrm{s}$.

The thermal rating design also needs to support the heating duty from delayed fault clearing during a breaker failure scenario. Given a fault on the line with a stuck breaker at Station A, the Station B terminal will interrupt its contribution normally within five cycles. Then fault will continue to be fed from Station A for an additional ten cycles, at which point the breaker failure scheme will clear Station A's contribution to the fault. We know from prior fault simulations that the Station A asymmetrical current contribution is 33.0 kA to an initial fault sourced from both terminals. By the time the Station B terminal opens, we consider the DC offset portion of the fault current waveform to have subsided, so Station A continues to contribute a symmetrical AC current of 30.7 kA, which we found earlier. From this two-step breaker failure clearing of the fault, the calculated thermal duty is $(33.0\ \mathrm{kA})^2\left({}^{5}/_{60}\ s\right) + (30.7\ \mathrm{kA})^2\left({}^{10}/_{60}\ s\right) = 90.8\ \mathrm{kA}^2\mathrm{s} + 157.1\ \mathrm{kA}^2\mathrm{s} = 247.9\ \mathrm{kA}^2\mathrm{s}$. It is also possible that the initial fault is cleared normally, but after reclosing back into the fault, a breaker fails to interrupt the fault the second time, and the fault has to be cleared on the second shot by the breaker failure scheme. This scenario would add approximately 90 kA^{2}s to the 247.9 kA^{2}s of heating of the single fault cleared by the breaker failure protection.

The thermal duties calculated earlier are far greater than the rating of the OPGW originally proposed by the transmission line engineering team to match the structural demand of the existing shield wire. The utility opted for the OPGW design withstand rating to not support the theoretical worst-case duty cycle of normal clearing of the initial fault followed by delayed breaker clearing of the fault after the final (and only) reclose attempt. The utility's justification was the low probably of the breaker successfully clearing the initial fault normally but shortly after failing to clear the fault after reclosing.

At this point in the study, there is a clear gap to resolve between the proposed OPGW thermal capacity of 109.0 kA^2s and the design thermal duty of 247.9 kA^2s. Also, the rating design still needs to include some margin for future fault current growth, as a current growth factor was not applied to the earlier calculations. Arrival at the final accepted design solution required both refinements to the short circuit study model and incorporating mitigation strategies that avoided substantial structure upgrades. Development of the final solution is discussed in the next section.

VII. MITIGATION DESIGN

After a detailed review of the study, the utility had several questions and further direction to refine the study and ultimately produce a design that satisfies the OPGW thermal duty, is constructible, and does not result in a significant increase in overall project cost. The most consequential of this feedback was a question about the short circuit model: how does the model account for the structure ground connections between the OPGW and earth? The line constants model from the utility's short circuit modeling software utilizes a simplified version of Carson's method, namely considering any grounded wires and earth to be at zero potential, effectively ignoring the grounded path between the OPGW and remote earth through the structure grounding design [6]. Therefore, the current return path for a ground fault is considered by the software to be the OPGW in parallel with earth of specified resistivity. The simplified earth return admittance model is not an uncommon practice for relay coordination short circuit modeling programs. However, the simplification prevents the model from indicating whether the structure grounds provide effective alternate paths to divert current from the OPGW and instead return through earth, thereby reducing the apparent OPGW current duty for a given fault. Answering this question required rebuilding the study model in an alternate system modeling software with the flexibility to model flow of fault current through more complex networks of impedances. For this case study, the Alternative Transients Program (ATP) was used and is referenced herein for convenience; other programs are available that possess the modeling and measurement capabilities needed for the analysis, and no endorsement is made for a specific modeling software.

Converting the model to ATP required reducing the original model to a boundary equivalent model, manually building the boundary equivalent model in ATP, simulating faults in both programs to verify equal simulation results, and then augmenting the ATP model with the structure grounds and other ground paths according to the design. Furthermore, the utility decided that a 10% fault current growth factor should be factored into the rating design, so the boundary equivalent source impedances at each end were reduced by 10% to increase all fault current outputs by 10%. Since the study is only interested in current flow along a single line, the ATP model was reduced to the line being studied, an equivalent source behind each end of the line, and a parallel transfer impedance connecting across the two end terminals. The original short circuit modeling software had a feature to automatically create the initial boundary equivalent system model, making the conversion of the study model to ATP a relatively simple and quick process. A one-line representation of a portion of the model is shown in Figure 1. Most of the work was spent re-modeling the studied line as a PI-equivalent line constants model, each span being modeled as a separate section, and the ends of the section being grounded through a structure footing resistance. The fault connection was modeled between the phase A conductor, OPGW, and structure. To verify accurate conversion of the model, fault simulation results were compared between models prior to adding the additional structure ground details to the ATP model.

The model of the structure grounding consisted of a resistance connected between the OPGW and ground at each structure. The utility's standard design resistance for 115 kV structure grounds is 15 ohms, which provides an important assumption to allow completion of lightning protection design studies prior to finalizing of structural designs. Satisfying the 15-ohm structure ground assumption requires that structure

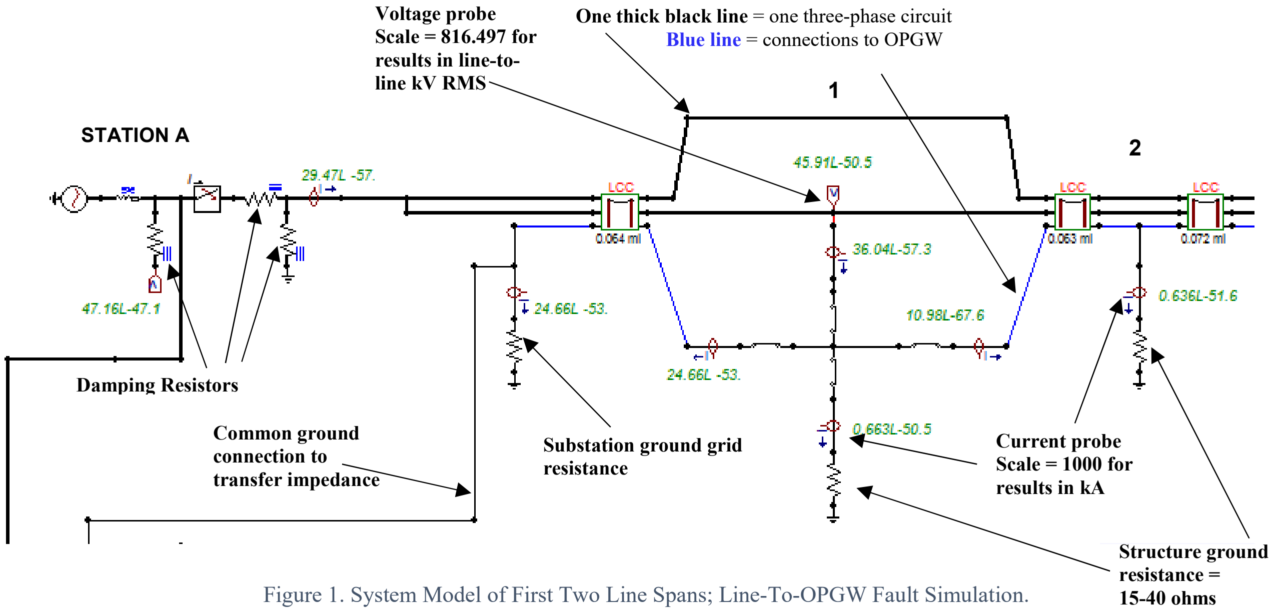

Figure 1. System Model of First Two Line Spans; Line-To-OPGW Fault Simulation.

grounding resistance is tested after the initial grounding design is installed, and further enhancements are made in the field as required to achieve a structure footing resistance of 15 ohms or less. Given prior knowledge of the area subsurface being composed of high-resistivity bedrock and soil, there was concern of a 15-ohm structure grounding system being practical to achieve and therefore assumed for the study. To address this concern, soil resistivity measurements were taken along the line, and the resulting soil was modeled in a program suited for studying electromagnetic effects. To this soil model, the utility's maximum standard grounding design was added, which is a 150-ft. long crow's foot counterpoise arrangement. This system included four ground rods located 10 feet from the structure with four 150-ft. counterpoise conductors spaced approximately 30 ft. from each other in either direction parallel to the line (Figure 2). Using this model, a nominal current was injected into the structure, and the total potential drop from the injection site to ground was recorded and used to calculate the equivalent structure footing resistance. Ultimately, the maximum standard structure grounding design only achieved an equivalent footing resistance of 40 ohms, so that value was entered as the resistance of each structure ground in the ATP model.

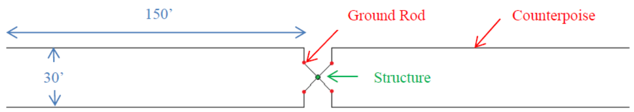

Figure 2. Structure counterpoise grounding arrangement.

Fault simulation results from the more granular study model indicated no significant change to the total current contribution to the fault through the Station A terminal, but the portion of ground current returning through the OPGW back to Station A was reduced to approximately 84% of the total current contributed by the Station A terminal. Each structure ground was off-loading the OPGW by approximately 600 A. The OPGW current duty was reduced to 24.66 kA for a fault on the first span out of Station A with both end terminals closed, and the DC offset multiplication factor was 1.008 given an OPGW current angle of -53° and a five-cycle integration period. With the Station B terminal open, the OPGW current was reduced to 24.13 kA. With these reduced apparent OPGW currents, calculating the thermal duty of a single fault event with failed breaker clearing yields $(1.008 * 24.66\ \mathrm{kA})^2\left({}^{5}\!/_{60}\ s\right) + (24.13\ \mathrm{kA})^2\left({}^{10}\!/_{60}\ s\right) = 51.5\ \mathrm{kA}^2\mathrm{s} + \ 97.0\ \mathrm{kA}^2\mathrm{s} = 148.5\ \mathrm{kA}^2\mathrm{s}$, a reduction in heating duty to $148.5/247.9 = 59.9\%$ of that indicated with the original short circuit model. The total heating duty still exceeded the capability of the proposed OPGW, so additional mitigation design strategies were studied.

Through discussions with the utility, a list of candidate mitigation strategies was approved for further study. From concern about any significant increases to project cost, the utility excluded the possibility of reconfiguring the pole top shielding design to support a second shield wire, which would add a second parallel conductor path for ground return current flow, reducing OPGW current duty by approximately 50% and overall heating by approximately 75%. The transmission line engineering team also confirmed that the currently proposed OPGW with thermal capacity of 109 $\mathrm{kA}^2\mathrm{s}$ is the largest that the structure tops can physically support. Therefore, the scope of mitigation design study work was narrowed to grounding design enhancements, reducing the breaker failure clearing time, and isolating the OPGW from the Station A and B ground grids.

GROUNDING DESIGN ENHANCEMENTS

The two grounding design enhancement strategies studied included 1) reducing the footing ground resistance to 15 ohms and 2) installing a continuous counterpoise grounding system.

Changing the structure footing resistance to 15 ohms did not appreciably change the available fault current for a close-in fault. The total OPGW return current, however, was reduced to 21.15 kA with both terminals closed and 20.79 kA with the Station B terminal open. The fault angle and DC offset heating factor were 54.7° and 1.012, respectively. With these reduced apparent OPGW currents, calculating the thermal duty of a single fault event with failed breaker clearing yields $(1.012 * 21.15\ \mathrm{kA})^2\left({}^{5}\!/_{60}\ s\right) + (20.79\ \mathrm{kA})^2\left({}^{10}\!/_{60}\ s\right) = 38.2\ \mathrm{kA}^2\mathrm{s} + \ 72.0\ \mathrm{kA}^2\mathrm{s} = 110.2\ \mathrm{kA}^2\mathrm{s}$. The total heating duty is nearly within the capability of the OPGW, but additional grounding design analysis showed that achieving 15-ohm footing resistance at each structure would require significant augmentation of the grounding design, either by deep ground wells or simply installing a continuous counterpoise grounding system. Since the standard lightning design was based on a 15-ohm footing resistance, additional lightning design analysis would need to be performed to ensure satisfactory performance with either 40-ohm footing resistances or a reduced footing resistance that can be achieved cost-effectively.

Installation of a continuous counterpoise system would provide a complete second conductor path for ground fault current and reduce the OPGW current and heating duties to well within its rating. A continuous counterpoise grounding system would also provide an effective path for lightning current, resolving concerns about needing to achieve 15-ohm footing resistances. Unfortunately, the right-of-way for the line intersects major roads in no less than six locations. Installing the continuous counterpoise across the road either as an overhead span or underground would require a major increase in overall project cost and permitting time, the latter of which was not acceptable given the project target in-service date. This enhancement option was therefore not approved for implementation.

REDUCING BREAKER FAILURE CLEARING TIME

Up to this point, the study assumed the breaker failure clearing time to be 15 cycles, matching the performance of the utility's standard breaker failure scheme, which is designed for breakers with three-cycle rated interrupting time. In this project application, the two end stations have 63 kA breakers with two-cycle interrupting capability. The utility had proposed reducing the breaker failure delay timer from the standard eight cycles to six cycles to reduce the breaker failure clearing time to 13 cycles. This change would still maintain a 3.75 cycle margin between a successful re-trip and a breaker failure trip. The effect on OPGW duty using the currents from the base design ATP model is $(1.008 * 24.66\ \text{kA})^2 \left({}^{5}/_{60}\ s\right) + (24.13\ \text{kA})^2 \left({}^{8}/_{60}\ s\right) = 51.5\ \text{kA}^2\text{s} +\ 77.6\ \text{kA}^2\text{s} = 129.1\ \text{kA}^2\text{s}$, a relatively safe 15% reduction in heating over the original design, but not enough to satisfy the capacity of the proposed OPGW without combining it with another means of mitigation.

ISOLATING THE OPGW FROM THE STATION GROUND GRIDS

One option proposed by the utility for study was isolating the OPGW from the ground grids at Stations A and B. Hypothetically, this change would increase overall zero sequence impedance of the ground fault and reduce available fault current, thereby also reducing OPGW duty. The OPGW would remain grounded at the remaining structures, and therefore the impact on line lightning protection performance would be negligible. By disconnecting the OPGW from the ground grids in the ATP model, the OPGW current for a fault in the first span from Station A is 21.29 kA ∠-38° with both line terminals closed and 18.29 kA ∠-46° with the Station B terminal open. Assuming the 13-cycle breaker failure design, the heating duty with isolated OPGW would be $(1.000 * 21.29\ \text{kA})^2 \left({}^{5}/_{60}\ s\right) + (18.29\ \text{kA})^2 \left({}^{8}/_{60}\ s\right) = 37.77\ \text{kA}^2\text{s} +\ 44.6\ \text{kA}^2\text{s} = 82.37\ \text{kA}^2\text{s}$, which is well within the thermal rating of the proposed OPGW. To physically implement such a change would require adding an insulator at the dead-end connection of the OPGW at the substation A-frame structure. The OPGW tail would be then trained down into an OPGW isolator assembly that resembles an underground cable termination and is used to transition the fiber tube out of the OPGW conductor body while maintaining isolation of the conductor body from the grounded substation A-frame. Alternatively, the OPGW tail can be trained down the A-frame using station post insulations to transition the fiber out of the conductor body within a fiber splice case mounted to another station post insulator. The ability of the isolator assembly to withstand a flashover during a ground fault is represented by its 60 Hz frequency wet withstand rating, which was just over 100 kV in this case. A station post insulator solution could implement greater insulation levels needed for applications with greater line voltages. The ATP fault simulation model indicated an OPGW peak potential rise at the fault point of 67.38 kV relative to ground with both terminals closed and 61.45 kV once the Station B end opens. The OPGW isolator was therefore suitable for the application, as would be a 38 kV-class strain insulator for the A-frame dead end termination. Given that the OPGW is a less effective ground path without the connection to the substation ground grids, this amount of OPGW voltage rise during a fault is expected, approaching the line-to-ground voltage as the impedance increases between the OPGW and ground.

The isolated OPGW option appeared initially to be a very effective option for reducing the OPGW current duty while requiring minimal infrastructure investment to implement it. However, some additional tradeoffs had to be addressed. Because the ampere limit to which the substation ground grid will remain IEEE 80 compliant will decrease by having one less alternate ground path connection, the substation grounding studies had to be reviewed for both designs. Fortunately, the substations' initial ground grids were designed to be compliant up to 63 kA, so the loss of one shield path only took out some margin of compliance, and the ground grid design remained compliant for the foreseeable future. The other complication was that the isolated OPGW design needed to be reflected in the line constants model for the utility's overall system short circuit model so that the protective relay settings will accurately discern in-zone versus out-of-zone faults. Representing the isolated ends of the OGPW was a single-span line constants model section at each end of the line that featured a "segmented shield," which effectively isolates the OPGW from the two end substation ground grids. A segmented ground wire is ignored in the software's series impedance calculations but is considered in the shunt-capacitance calculations. The short circuit model software used by the utility also does not account for the structure grounding at all, rather treating the ground fault as connected in parallel with the OPGW and earth defined by its resistivity. The earth resistivity could be used as a tuning parameter to make the short circuit results from the utility short circuit software more closely match that of the ATP model, although this is a preliminary suggestion and requires further investigation to understand the practicality and tradeoffs to this approach. Other available short circuit modeling programs model the structure footing grounds with specified resistance as a distributed parameter and would be expected to more accurately match the results from the ATP model of the isolated OPGW and detailed structure grounding.

CONCLUSION

Addition of an OPGW to a transmission line can require extensive and iterative analyses of fault current duty, the line structural design, and even the structure grounding design to ensure that an OPGW will not anneal and fail due to thermal overload. Especially when the fiber within the OPGW is relied on for critical communications applications like line teleprotection and SCADA, it is important to prevent an OPGW failure because it does not lend to a practical mid-span splice repair option. Introducing fault current duty calculations as soon as possible into the overall design process, even during the scoping and planning phase of a project, would help a utility to develop a line design that can cost-effectively satisfy the thermal duty of the OPGW application. If the OPGW thermal duty is accounted for later in the design process, fewer options are available to augment the line design to satisfy the thermal duty. Mitigation options are available that can help reduce the OPGW thermal duty, and this paper discusses the process and techniques for developing a few different mitigation strategies.

ACKNOWLEDGEMENT

The author would like to thank fellow POWER Engineers colleagues Andrea Wood, Joe Mooney, and Jon Leman for their contributions to this paper and the original case study.

REFERENCES

[1] IEEE 738-2012 – Standard for Calculating the Current-Temperature of Bare Overhead Conductors, Section 4.2.3.

[2] Dale L. Johnson and William W. Vaughn, “Lightning Characteristics and Lightning Strike Peak Current Probabilities as Related to Aerospace Vehicle Operations,” in Proceedings of The Eighth Conference on Aviation, Range, and Aerospace Meterology, Dallas, TX, 1999, p. 3.

[3] C62.11-2012 IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (> 1 kV).

[4] Alan Greenwood, Electrical Transients in Power Systems, Second Edition, John Wiley & Sons, Inc., 1991, pp. 37-41

[5] Larry L. Henrisksen, Jon T. Leman, Brian H. Berkebile, “Fault Current Rating of Optical Ground Wires”, proceedings of the POWER Engineers, Inc. Line Conference, March 2008, p. 4.

[6] H. Dommel, "Overhead Line Parameters From Handbook Formulas and Computer Programs," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 2, February 1985.

BIOGRAPHY

Ryan McMaster has been a consulting engineer for electric utilities for the past 11 years, joining POWER Engineers in 2013. He is a member of the SCADA and Analytical Services group, where he performs a variety of electrical system studies for transmission, substation, and generation projects. He has a background in protective relaying and substation protection and control design. Ryan received his B.S. in Electrical Engineering from Washington State University.