Weak Infeed Study and Protection Solution

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Abstract

This paper makes a more detailed study of system weak infeed, and further defines and analyzes both conditional and unconditional weak infeed in theory and their protection solution in engineering application. Starting from a system circuit model and derived function of fault impedance, it revealed that fault location would contribute impact on both source impedance and short circuit impedance, and also on conditional weak infeed scenario. For unconditional weak infeed this paper analyzed the typical system configuration and types of power sources that may provide lower fault current to form innate weak infeed scenario.

Based on different types of weak infeed, the corresponding protection solutions are analyzed accordingly. Especially for unconditional weak infeed, protection scheme is typical interconnection protection. It shall include main protection and independent local backup protection. Its relay settings should coordinate with utilities grid protection to meet both sensitivity and security requirements.

1. Introduction

Weak infeed or weak source scenario occurs only under fault condition. But this system configuration may exist under condition of normal system operations or some kind of outage operations. Generally there are two kinds of weak infeed scenario, conditionally and unconditionally, depend on system configuration and types of power sources.
The truth of weak infeed is fault impedance, the sum of source impedance and short circuit impedance, is higher and power sources can’t provide reliable fault current for relay current related elements detecting the fault. An interesting issue is fault impedance is a variable function of system operation, and especially fault location within the protection zone. Under a given system condition fault impedance is nonlinearly proportional to fault location. For close in fault it is the minimum and for remote end fault it is the maximum.

Conditional weak infeed occurs in complex system configuration and is dependent on fault location. Protection for conditional weak infeed is included in line protection schemes that apply manufacturer’s typical logics generally.

Unconditional weak infeed occurs mainly with IPP (Independent Power Producers) connection to the system. For the innate features of IPP sources, its equivalent source impedances may limit to provide fault current to some extent for external faults in grid. Protection for unconditional weak infeed is not included in line’s protection schemes generally, but practiced as a way of interconnection protection. The protection should include two parts, the main protection from utilities line's ends, and independent IPP local backup protection.

2. General study in system circuit model, impedances, SFR and fault current

2.1 System circuit model

The general system circuit model used for analysis is shown in Figure 1, in which two equivalent power sources (ES and ER) are connected to two terminals (S and R) with innate source impedances (ZS and ZR) and two parallel lines are in between two terminals. Line ZL is the line for analysis, and line ZD is the equivalent line. This equivalent model can be got from any complex system configuration by analytical software.

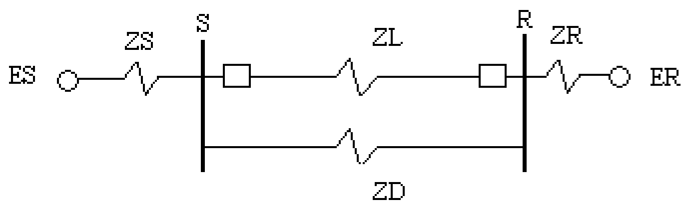

Figure 1

For the purpose of source impedance derivation under system fault condition, it is assumed that the interested relay location is in line L at S terminal; and a three phase to ground bolted fault (3LG) occurs at a specific point k on the protected line, as shown in Figure 2. k is the percentage of ZL with a value between 0 and 1.

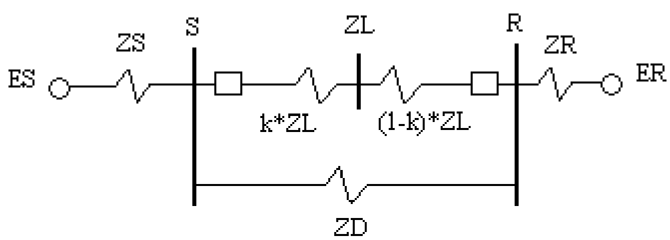

Figure 2

2.2 Source impedance, short circuit impedance and fault impedance

From Reference 2, the system circuit can be derived from Figure 2 to Figure 3 and the final equivalent system source impedance can be expressed in equation (1).

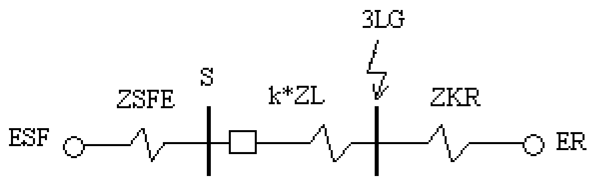

Figure 3

ESF is the final equivalent source potential. Generally assume ESF=1.
ZSFE is the final equivalent source impedance for the fault.
ZKR is the equivalent impedance from remote source to fault location.

$$ZSFE(k)=\frac{ZS*\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}{ZS+\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}*[1+\frac{k*ZL}{\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{ZR}}] \qquad (1)$$

The final equivalent system source impedance ZSFE behind the relay is valid for forward faults. It is the apparent impedance considering infeed effect of remote source and outfeed effect of local source. It is a function of fault location on the protected line in nonlinearly proportional. The farther the fault location, the higher the equivalent system impedance will be. An example curve of source impedance is shown in Figure 4.

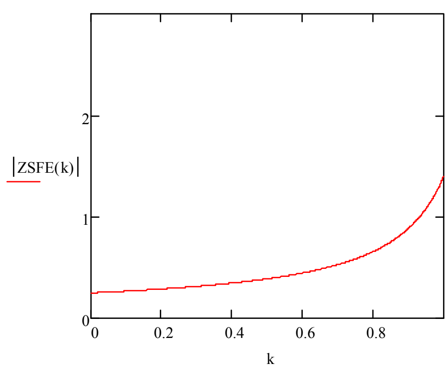

Figure 4

The line short circuit impedance between bus and fault location is $ZSC(k)=k*ZL$. It is a function of fault location on the protected line in linearly proportional. An example curve of short circuit impedance is shown in Figure 5.

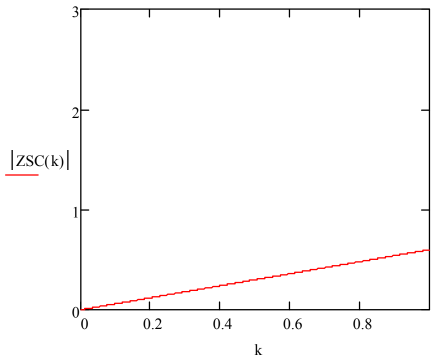

Figure 5

The total fault impedance is the sum of source impedance and line short circuit impedance in equation (2).

$$ZF(k)=ZSFE(k)+ZSC(k)$$
$$=\frac{ZS*\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}{ZS+\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}*[1+\frac{k*ZL}{\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{ZR}}]+k*ZL \qquad (2)$$

Similar to source impedance, fault impedance is a function of fault location on the protected line in nonlinearly proportional. An example curve of fault impedance is shown in Figure 6.

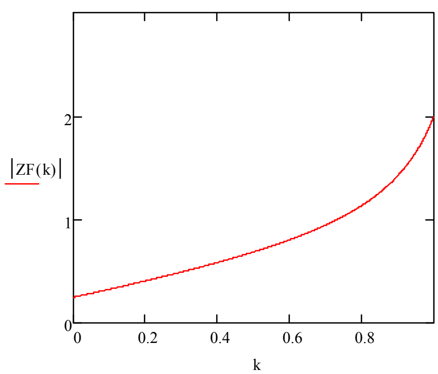

Figure 6

2.3 SFR

SFR is the line short circuit impedance-to-fault impedance ratio. SFR can be expressed in equation (3) and an example curve is shown in Figure 7.

$$SFR(k)=\frac{ZSC(k)}{ZF(k)}=\frac{1}{\frac{ZS*\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}{ZS+\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}*[\frac{1}{k*ZL}+\frac{1}{\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{ZR}}]+1} \qquad (3)$$

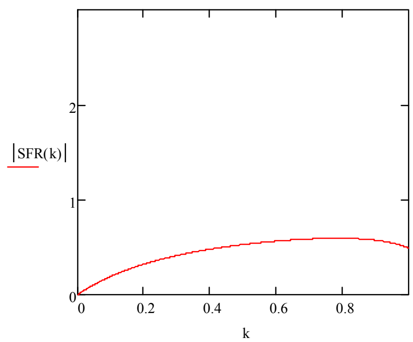

Figure 7

In Figure 7 SFR (k) also shows phase voltage curve at bus S (relay location). For close in fault phase voltage will be the minimum. But for transmission line the maximum bus voltage generally does not occur for a fault at the remote end of protected line, it could be at one point on the line. This can be got mathematically by solving the derivative of $\frac{d(SFR(k))}{dk}=0$. For radial line, the maximum voltage should be at the end of line in $SFR(1)$.

The suitable phase under voltage element setting should be set more than the possible maximum fault voltage at bus. So this realization will be helpful to the phase under voltage element setting for conditional weak infeed scenario.

2.4 Fault current

The fault current magnitude in PU value can be got in equation (4), in which assume the final equivalent source potential ESF is 1.

$$IF(k)=\frac{ESF}{ZF(k)}=\frac{1}{ZSC(k)+ZSFE(k)}$$

$$=\frac{1}{k*ZL+\frac{ZS*\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}{ZS+\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}*[1+\frac{k*ZL}{\frac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{ZR}}]} \qquad (4)$$

Equation (4) reveals that fault current is a function of fault location in the protected line in nonlinearly inversely proportional. The farther fault location, the higher short circuit impedance and source impedance, the higher fault impedance and lower faults current will be. So fault location contributes double impacts on fault current. An example curve of fault current is shown in Figure 8.

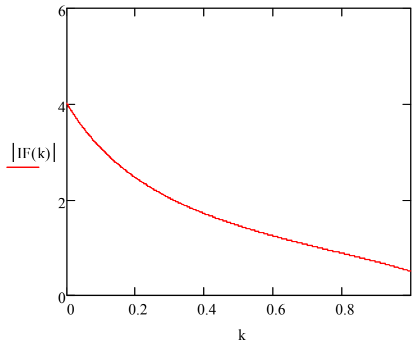

Figure 8

2.5 Parameters for the sample of function curves
The functions curves in Figures 1~8 are implemented in MathCad.

$$\angle(mag, ang) = mag * (\cos(ang.\text{deg}) + j * \sin(ang.\text{deg}))$$

Assume

$ES = 1.05\angle 30$	$ER = 1\angle 0$
$ZS = 0.35\angle 85$	$ZR = 0.5\angle 83$
$ZL = 0.6\angle 80$	$ZD = 0.2\angle 82$

3. **<u>Conditional weak infeed and protection scheme</u>**

3.1 Conditional weak infeed
This kind of weak infeed scenario generally takes place in a complex system configuration with ZD<∞ and related to fault location with k>0.

The performance of weak infeed is that fault current is not high enough to pick up the relay. In this paper only consider system's impact on relay's operation. Fault location (k) is the only factor to affect fault current.

From the formula (5) in Reference 3, the CT size can be determined for no time delayed distance zone 2 element correctly pickup, assumed to be CTratio. CTratio may be got from others suitable ways.

Assume relay current pickup at CT's secondary side is Irelaypickupsec that can be got from relay manual. Ibase is the base current corresponding to voltage level. Relay current pickup at CT's primary side is

$$Ip = \frac{\text{Irelaypickupsec} * \text{CTratio}}{\text{Ibase}} \qquad (5)$$

This can be treated as a known value for a specific study.

From Figure 8 it is possible to check if $IF(k)=Ip$ exists in the curve. Or take $IF(k)=Ip$ to solve k. If $0 \le k \le 1$, there is weak infeed and the exact weak infeed location can be got under a given system condition.

Practically for this kind of weak infeed a simple way is to consider the condition of k=1, the maximum fault impedance, the minimum fault current, so the best condition for weak infeed to exist. If it is not weak infeed for fault at remote end, there will not be any weak infeed scenario for this line.

From equation (2), there is

$$ZF(1)=ZS*(1+\frac{ZL}{ZD})+ZL \qquad (6)$$

Consider necessary margin factor of m that involves the times of three phases fault current to two phases fault current or one phase to ground fault current assuming three phases fault has the maximum fault current, from equation (4) there is

$$IF(1)=\frac{1}{ZF(1)}=\frac{1}{ZL+ZS*(1+\frac{ZL}{ZD})} \le m*Ip \qquad (7)$$

$$\frac{1}{Ip*ZF(1)} \le m \qquad (8)$$

Or

$$\frac{IF(1)}{Ip} \le m \qquad (9)$$

This can act as conditional weak infeed criteria in engineering.

3.2 Protection scheme for conditional weak infeed

For conditional weak infeed happened in a complex system configuration, this protection should be included in line's protection scheme. The general way is to apply manufacturer standard logics for it, such as POTT, differential scheme, or even DCB scheme. IEEE Std C37.113-1999 has detailed protections applied for this weak infeed scenario.

It is necessary to note the settings of voltage elements used in the standard logics. For the logics in manufacturers or utilities application protection signals exchange with remote ends by teleprotection communication, the voltage elements settings in the logics just need to consider the sensitivity for entire protected line, not in security coordination.

Under condition of the equivalent source impedance is not much higher than line's impedance as shown in Figure 9, the SFR will not be lower in this scenario. The voltage at bus may not be low enough and the under voltage element default settings from manufacturer may not be effective to detect faults. Further, the maximum bus fault voltage may be from any fault point on the protected line, as mentioned in section 1.3 in this paper, so the voltage elements settings should be considered according to the real system fault calculation.

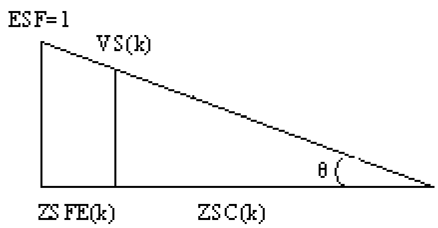

Figure 9

4. <u>Unconditional weak infeed analysis</u>

4.1 Unconditional weak infeed

This kind of weak infeed has two characteristics, IPP sources that may behave as innate weak sources, and its “injection”connection way that looks like to be “injected” to grid. Generally smaller capacity IPP is tapped into utilities transmission or distribution lines; bigger capacity IPP may be connected to grid bus directly due to its possible fundamental impact on systems. In the standard system circuit model Figure 1 there is ZD =∞ for this kind of weak infeed.

IPP generators may have innately higher subtransient impedance, the sources can’t provide enough faults current, but provide fault current still. So the current related elements, such as over current elements, distance elements will not pickup. The only way to detect fault is to apply voltage elements for this case. Luckily due to source impedance is higher so the SFR is lower. The bus voltage will be changed significantly and the voltage element can be effective to detect the lower current fault.

For this weak infeed is totally due to weak source and its interconnections, not related to grid at all, it is reasonable to consider the condition of k=0 only. From equation (1) and (3), there are

$$ZSFE(0)=ZS \quad (10)$$

$$IF(0)=\frac{1}{ZS} \leq m*Ip \quad (11)$$

Or

$$\frac{IF(0)}{Ip} \leq m \quad (12)$$

This means that unconditional weak infeed may even occur for a line’s close in fault due to higher source impedance ZS, as IEEE Std C37.113-1999 stated.

4.2 Unconditional weak infeed sources provided faults current analysis

Generally there are three types of generators in IPP, which may make unconditional weak infeed scenario. They are synchronous, induction and inverter generators.

4.2.1 Synchronous sources
Synchronous sources may provide very low fault current to external faults. This may be due to smaller capacity, or frequent in service or out of service switching. The magnitude of fault current will vary after faults occurring. In initial subtransient interval its magnitude is determined by X"d, and then go to transient (X') and steady interval (Xd). The magnitude will be decaying gradually. The decay rate will be dependent on short circuit subtransient direct axis time constant (T"d) and transient direct axis time constant (T'd).

Sometimes this kind of source can't provide sustained reliable fault current for current elements faults detecting.

4.2.2 Induction sources in wind plants
From Reference 5 the contribution from induction sources to external faults during the initial cycle of the fault can be as high as six times of the rated load current or more, but this decays quickly in two or three cycles as the fault persists, similar to induction motors. This is due to induction generator consumes reactive power under operation condition and the air gap flux will collapse without sufficient line voltage support after fault, especially for three phases to ground fault.

This kind of source may not provide reliable fault current for relay elements faults detecting in both magnitude and fault duration.

4.2.3 Full-converter wind turbine generator in wind plants
The feature of this kind of sources is the fault current can be limited to its rating or a little above its rated load current and the fault current provided to grid is balanced and symmetrical regardless the type of external fault.

This source is similar to the induction source that may not to provide reliable fault current.

4.3 Impact of interconnection transformer connections on interconnection protection
The main concern is whether there is any zero sequence current to flow through IPP interconnection transformer for one phase to ground fault in external grid. It depends on interconnection transformer winding connection. To avoid over voltage imposed on IPP caused by one phase to ground fault after utility source is cleared, the general practice is to apply the interconnection transformer to be Y grounded at high voltage side and delta at low voltage side.

5. <u>Unconditional weak infeed protection scheme</u>

5.1 Tapped connection weak infeed protection scheme
This is the connection applied for smaller capacity IPP and the protection scheme is the interconnection protection practice.

Generally interconnection protection at IPP end is not involved in line's protection scheme. The feasible interconnection protection scheme should contain two parts described as follows.

5.1.1 Main protection should be remote transfer trip from utility's ends.

5.1.2 Consider the main protections are out of service, it has to have independent local backup protection that should not be any current related elements. The general practice is to apply voltage elements that should have voltage input from system high voltage side. For grounded interconnection transformer connection, phase under voltage element (27) is good enough to be the weak infeed protection. For high voltage side ungrounded interconnection transformer connection, except phase under voltage element (27), it is necessary to apply zero sequence over voltage element (59N) as weak infeed protection, which is effective for one phase to ground fault. Figure 10 is a typical logic for this situation in which Z3P and Z3G are distance elements looking into to IPP side.

Different from the voltage elements in conditional weak infeed protection, the voltage elements for unconditional weak infeed need to not only considers the sensitivity for entire protected line, but also the security to coordinate with its downstream utilities protection scheme. For this unconditional weak infeed occurs in simple injection interconnection system configuration, after utilities ends tripped, the remaining IPP and its connection line will become a typical radial line. The maximum bus fault voltage should be from the fault at the end of the line as mentioned in section 1.3 in this paper. For the security of this voltage element it is suggested to add some time delay. Due to IPP special connection way to systems, the added time delay will not have any impact on system's transient stability and can be accepted.

The purpose of unconditional weak infeed protection at IPP end is for isolating the faults within the protected zone. A successful line reclose may restore the line from utilities end after the isolation.

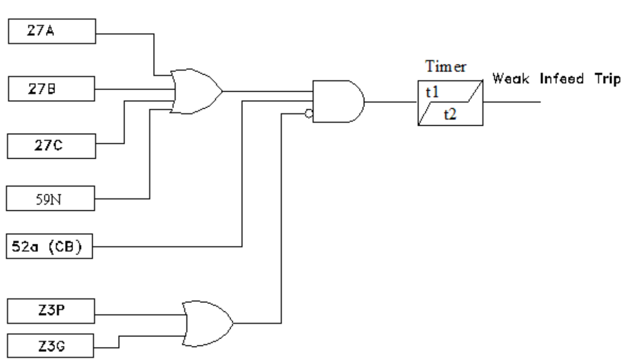

Figure 10

5.2 Transmission connection weak infeed protection scheme

IPP with bigger capacity will be connected to grid via a transmission line. The protection scheme is the same as conditional weak infeed. But it is better to implement the independent IPP local backup protection stated in section 5.1.

6. <u>Conclusion</u>

6.1 There are two types of weak infeed, conditional and unconditional. Both are different in their system configuration.

The performance of weak infeed is fault source can not provide enough fault current for current related protection elements to pickup.

6.2 Conditional weak infeed occurs in transmission line, or complex system. It depends on fault location on the protected line. Two impedances make impact on conditional weak infeed. One is system source impedance behind the bus, another one is short circuit impedance in front of the bus.

The truth of conditional weak infeed is that fault impedance, the sum of both source impedance and short circuit impedance, is higher.

Practically equation (9) is applied for checking the fault at the remote end of protected line for conditional weak infeed. If it doesn't perform weak infeed at the remote end, the line will not be weak infeed.

Conditional weak infeed protection should be included in line typical protection scheme. The voltage elements in the scheme should have enough sensitivity for entire line. But for the maximum bus voltage may occur at a variable point on the line, it is necessary to do the fault calculations case by case for phase under voltage element settings.

6.3 Unconditional weak infeed is due to a special system configuration in which IPP is "injected" to grid.

The truth of unconditional weak infeed is source impedance is higher, just as IEEE Std C37.113-1999 stated.

IPP may be various types of synchronous, induction or full converter sources.

As local independent backup protection at IPP end the only way to deal with unconditional weak infeed is to implement phase under voltage elements or "plus" zero sequence over voltage elements that measure voltages from grid side PT. The voltage elements should have enough sensitivity for the entire line and security to coordinate with its downstream line's protection in utility ends. The maximum bus voltage should be got from the fault at the end of the line after utilities end tripping. The security should be achieved from the added time delay.

<u>Acknowledgement</u>

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