Windfarm System Protection Using Peer-to-Peer Communications

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1. Introduction

Windfarm electrical systems present some unique challenges for protection. The grid tie and wind turbine generators provide multiple sources of fault currents to be considered. Collector feeders become isolated ungrounded systems during faults due to separation from the centralized collector bus reference ground. Ground faults on feeders will result in unfaulted phase voltages rising to line levels. In addition, severe transient overvoltages can be produced, which can degrade insulation resulting in eventual equipment failure.

This paper reviews the overall requirements for comprehensive windfarm protection. It also focuses on the particular problem of feeder ground faults. A novel, yet simple solution is presented that makes use of peer-to-peer (GOOSE) messaging via the IEC61850 protocol. The characteristics of the GOOSE message are discussed with respect to speed and reliability and communications architecture is presented. The performance of the resulting protection scheme is quantified.

2. Wind-Turbine Protection Considerations

The type of wind turbine unit will have some bearing on the protection requirements. There are several Wind Turbine Generator (WTG) configurations in commercial operation today. This discussion focuses on the doubly fed induction generator (DFIG). Figure 1 shows a single line diagram of a typical WTG and the location of the IED.

In this configuration a variable-pitch wind turbine is connected through a gearbox to a wound rotor induction machine. Back-to-back voltage-sourced converters are used to connect the rotor circuit to the machine terminals in order to provide variable speed control. The WTG step-up transformer has three windings. The high voltage winding is delta connected. Both LV windings have grounded-wye connections. One LV winding is connected to the stator circuit, the other to the rotor circuit. The high voltage winding of the transformer may be connected to the grid through a circuit breaker or through fuses.

Stator ground faults on the LV side of the WTG transformer are not detectable by upstream protections due to the transformer connection. The IED provides protection for these faults using an instantaneous overcurrent element. This element may respond to zero sequence, residual current, or transformer neutral current. The element requires no coordination with other protection elements, allowing it to operate with minimal time delay. If the element is measuring zero sequence via the phase currents or the residual current connection, then possible CT saturation during external faults should be considered when determining the pickup setting.

The IED also provides protection for LV phase faults. An instantaneous element will interrupt severe faults with minimal delay. Note that the DFIG will provide a contribution to external faults. This element should be set lower than the minimum current expected for a phase fault at the generator terminals and above the maximum expected generator contribution to a fault on the network. A time overcurrent element will detect phase faults internal to the generator. Upstream time overcurrent protections should coordinate with this element.

An IED with similar protection elements can also be applied to the converter circuit. This IED can detect faults up to the converter terminals but cannot detect faults in the rotor winding.

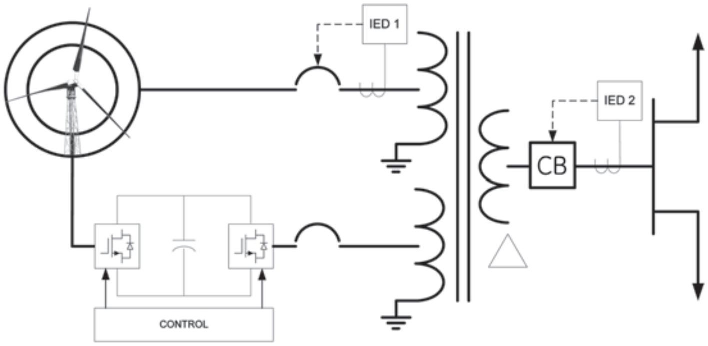

Figure 1.
WRG Single Line

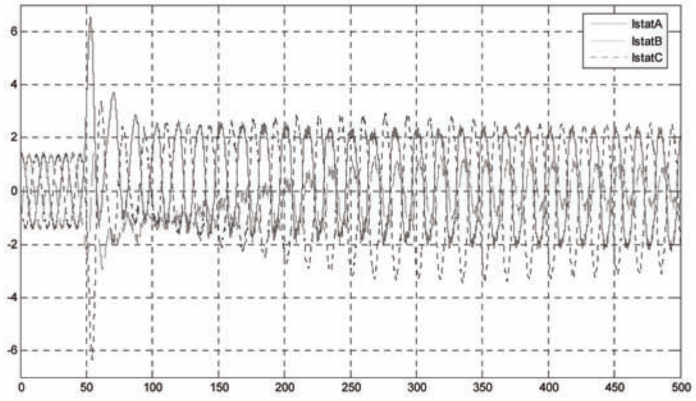

Figure 2.
Simulation of WTG contribution (pu) to an external ground fault

Auxiliary protective functions are also required for the DFIG. These protections may be embedded into the WTG controller or alternatively may be implemented within the IED. These include:

- Voltage unbalance
- Overheating (RTDs)
- Reverse phasing
- Poor synchronizing
- Voltage and frequency out of limits

The WTG also must be capable of isolating itself from a fault on the feeder. Ideally, this should be done with minimal delay. At the same time external fault protection should never operate for faults on adjacent feeders or on adjacent WTGs. Practically, it is not possible to achieve this level of performance solely through measurement of local currents and voltages. Typically, grid fault detection relies on undervoltage and overvoltage elements. These elements are delayed to allow upstream protection to open the feeder breaker, thereby preventing a trip for fault on another feeder.

Finally, the WTG IED should have the abilities to capture voltage and current waveforms and sequence-of-events data during a fault or disturbance. These are valuable tools for fault analysis and verification of protection system performance.

3. Windfarm Substation Protection Considerations

Figure 2 shows the single-line diagram of a typical wind farm. Several feeders terminate at the collector bus. A power transformer steps up the voltage to the transmission level. A single HV transmission line connects the windfarm to the grid.

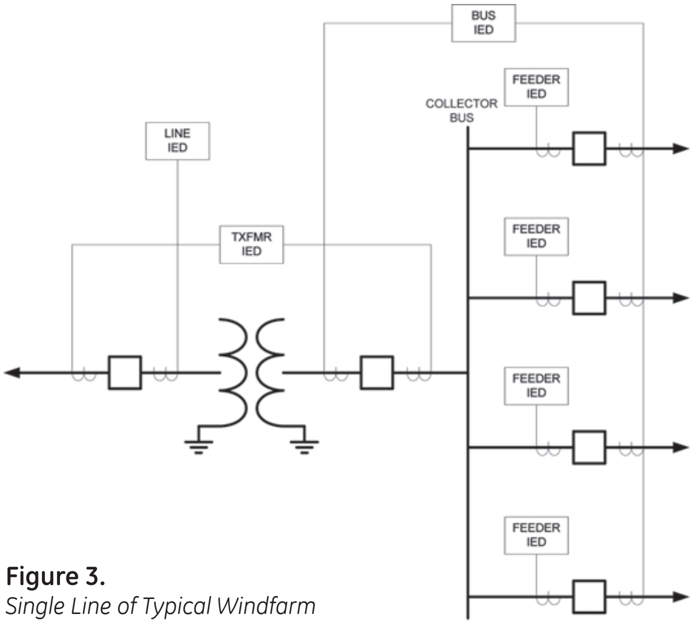

Figure 3.
Single Line of Typical Windfarm

Protection is required for the collector bus. A high or low impedance differential element will produce the fastest clearing times for bus faults. If a low impedance bus differential scheme is used, then the feeder CT should not be paralleled. Otherwise the WTG fault contribution can produce a false operation if CT saturation occurs during an external fault.

A blocking scheme can be applied as an alternative to the bus differential. An overcurrent element in each of the feeder IEDs sends a blocking signal to an overcurrent element located in an IED on the transformer breaker on the occurrence of a downstream fault. When a bus fault occurs, no blocking signals are sent. GOOSE messaging, discussed in detail below, over the substation LAN provides a convenient method of exchanging the blocking signals.

Protection is also required for the power transformer. This will take the form of a percent differential element with inrush inhibit. If the number of feeders is low then the bus and transformer zones may be combined using a multi-restraint transformer differential element. This allows the transformer breaker and CTs to be eliminated.

The windfarm may be interconnected to the grid via a two terminal transmission line or it may be tapped onto a multi-terminal line. In either case the protection of the transmission line typically takes the form of line differential or distance elements. Each scheme will require a dedicated communication channel linking the windfarm to the remote utility terminal(s) to provide optimum protection. A communications channel can also be used to signal to the utility terminal that the windfarm has been disconnected and that reclosure is permissible. Out-of-phase reclosing onto the windfarm will produce severe torque transients and must be avoided.

Reclosing for ground faults can be implemented in the case that single-pole tripping is employed. In this scheme the windfarm remains synchronized with the grid through the healthy phases. This will increase the availability of the windfarm but requires protective IEDs and circuit breakers that are capable of single-pole operation.

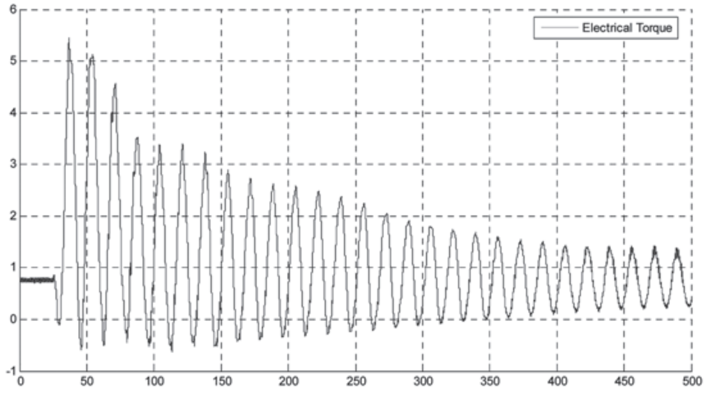

Figure 4.
Simulation of WTG Torque due to Reclosing Out-of-Phase

4. Windfarm Feeder Topologies

There are several types of feeder topologies currently applied in windfarms. Radial, bifurcated radial, feeder-subfeeder, and looped topologies are the most common types used, each yielding their own distinct advantages and disadvantages. These factors and other criteria such as wind profiles, available tower placement, costs, etc. must be considered in order when determining which topology to use.

Radial collector system topologies are comprised of a single feeder circuit originating from the collector bus and connecting sequentially to each WTG tower. It provides the least complex feeder configuration and is best suited in applications where linear WTG placements are well defined. It has a lower installed cost per feeder due to the low complexity. Inter-tower cable faults or WTG faults can be isolated to allow continued production. However, a station circuit breaker failure or a cable fault between the station and first tower result in complete loss of all feeder generation, which makes it one of the least reliable.

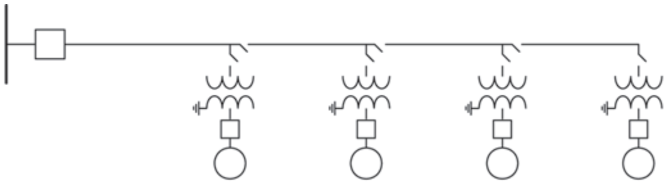

Figure 5.
Radial Feeder

Bifurcated radial topologies are similar to the radial system except they use one collector bus circuit breaker to switch two collector feeders. This configuration has the lowest installed cost base per feeder. However, it also has the lowest reliability because a breaker failure or a cable fault between the station and first tower result in complete loss of both feeders' generation.

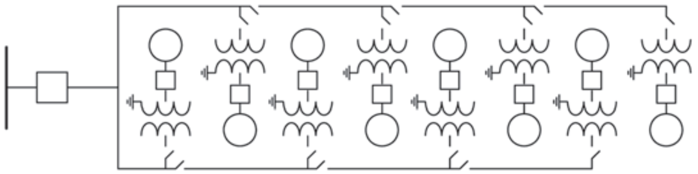

Figure 6.
Bifurcated Radial Feeder

Feeder-subfeeder topologies are typically employed where clusters of towers are distributed over large areas. They are typically comprised of a single cable feeding remotely located switchgear with several subfeeders.

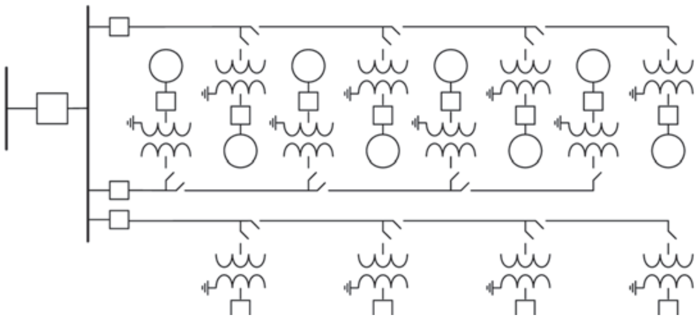

Figure 7.
Feeder-Subfeeder

Looped feeder topologies provide a higher level of availability when compared to the others. It allows continued production in the event of single component failures. Faults in the WTG tower or between towers can be isolated, allowing the remaining WTGs to continue production.

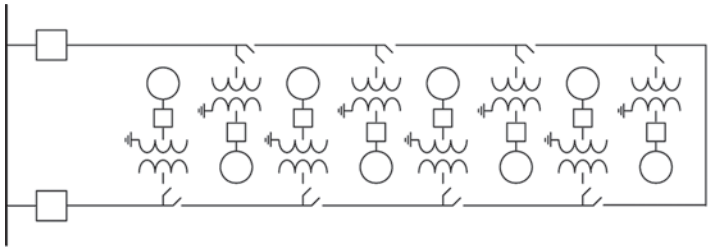

Figure 8.
Looped Feeder

5. Limitations of Typical Windfarm Topology

All windfarm topologies have an inherent limitation common to the collector bus – feeder arrangement. The windfarm topology is connected to a collector bus and stepped up to transmission level voltage through a power transformer. The windfarm feeders rely on the substation transformer neutral-ground connection for a reference ground for the medium voltage collector system. The WTGs cannot provide a reference ground because of the WTG transformer delta connection. A grounded WYE connection would introduce multiple sources of ground fault current that will complicate the ground fault protection and desensitize the IED at the substation.

If a feeder circuit breaker opens during operation, then that feeder and the operating WTGs will become isolated and form an ungrounded power system. This condition is especially troublesome if a phase-to-ground fault develops on the feeder; a scenario that causes the unfaulted phase voltages to rise to line voltage levels. It should be pointed out that a feeder ground fault is the most commonly anticipated fault type for on-shore windfarms that use overhead lines for the feeders. This fault can also result in severe transient overvoltages, which can eventually result in failure of insulation and equipment damage.

Under Normal Conditions

$V_A = V_N \angle 90°$

$V_B = V_N \angle -30°$

$V_C = V_N \angle -150°$

Grounded System under A-G Fault Conditions

$V_A = 0$

$V_B = V_N \angle -30°$

$V_C = V_N \angle -150°$

Isolated System under A-G Fault Conditions

$V_A = 0$

$V_B = \sqrt{3} \cdot V_N \angle -60°$

$V_C = \sqrt{3} \cdot V_N \angle -120°$

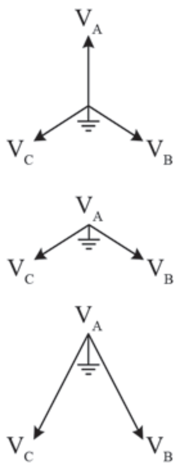

Figure 9.
Relationship for Normal and Fault Conditions

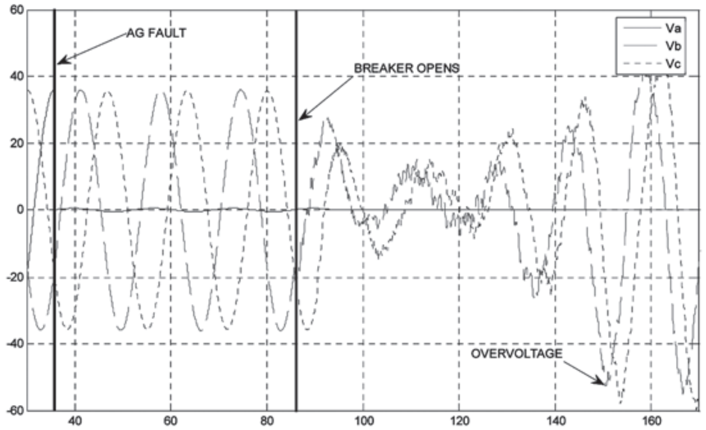

Figure 10.
Simulation of Feeder Overvoltage During a Ground Fault

Ignoring this condition could produce eventual failure of a cable or WTG transformer. One remedy is to design for the ungrounded system. This results in increased costs due to the higher voltage ratings, higher BIL, and added engineering. Another solution is to install individual grounding transformers on each feeder. This adds to equipment and engineering costs and increases the substation footprint.

6. Coordinated Fault Clearance via Transfer Tripping

An alternative solution is to disconnect the WTGs from the feeder before tripping the feeder breaker. However, the IED protecting the feeder in the substation is the only IED that can selectively detect feeder faults. In this case this IED would then send a transfer trip to all WTGs on the feeder. Once all units are disconnected, opening of the feeder breaker results in a well-behaved collapse of the voltage. Opening of the feeder breaker would be delayed minimally to ensure coordinated tripping.

7. Transfer Trip Implementation

The proposed method for implementation of the transfer trip solution is IEC61850 GOOSE messaging over a fiber-optic Ethernet network. This solution supports critical signaling to multiple IEDs. IEDs connect directly to the network, removing the need for expensive teleprotection equipment. Windfarms are often designed to include an integral network of optical fiber. Off-the-shelf Ethernet switches are available that can be configured to the existing fiber layout and can easily accommodate the distance between IEDs. As an added benefit, fiber-optic media provides excellent immunity to noise or ground potential differences.

Adoption of the IEC61850 protocol allows the same communication path to be utilized to transmit a variety of additional data. Examples of this information include control commands between devices for issuing of trip from other substation protections, commands to preclude a device from otherwise tripping (blocking), interlocking the control of a device with status of another device, event and diagnostic information (such as waveforms and event logs), and analog information (such as current and power metering).

This protocol supports several important features that make it an appropriate choice for this application. Any data items in the IED that are available via IEC61850 are structured according to the protocol and include standardized descriptions of the source and type of the data. The IEC GOOSE message carries a “user defined” dataset. The dataset can be configured with IEC61850-modeled data items. The methodology promotes ease-of-configuration and interoperability between various manufacturers IEDs.

GOOSE is a multicast message that, once transmitted can be received by any device on the network that needs it. A feature supported in the IEC GOOSE is the ability to restrict the flow of data to a particular broadcast domain through the creation of a Virtual Local Area Network or VLAN. This dataflow restriction is achieved by adding 4 bytes to the Ethernet data frame per the IEEE802.1Q standard (Figure 8). A 2-byte Tag Protocol Identifier identifies the extended data frame. The other 2 bytes include 12 bits for a VLAN ID, 3 bits for priority encoding of the Ethernet message, and one bit for backward compatibility with Token Ring. Once identified as an extended Ethernet frame, a switch in the network can decode the VLAN ID or VID. This ID is read by the network device and “switched” to those ports programmed with the same VLAN ID.

Another area addressed by the IEC GOOSE is that of Ethernet Priority. Ethernet communication has been traditionally described as “non deterministic” in that the possibility of collisions on the wire made it difficult to determine the delivery time of the message. The use of Layer 2, full-duplex switch technology now prevents the occurrence of Ethernet collisions. Switches receive all messages and store then forward them to the destination locations as required. It is possible for a single port in the switch to have several messages queued for delivery to a device. This would add a certain amount of delay in the processing of a message. Ethernet Priority, however, removes this delay. Upon receipt of an Ethernet message with a “high priority”, the message is moved to the front of the queue and becomes the next message to be sent to the receiving device thereby minimizing the transmission time of the message.

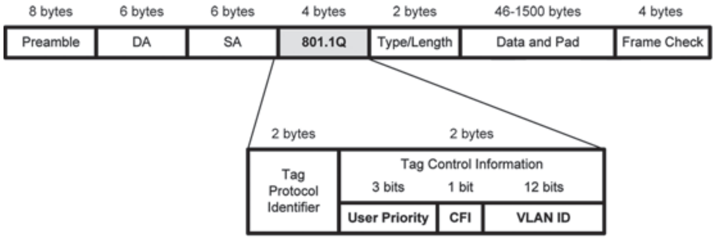

Figure 11.
Extended Ethernet Frame

The diagram below shows how the IEC61850 network topology would be deployed for a larger, radial windfarm;

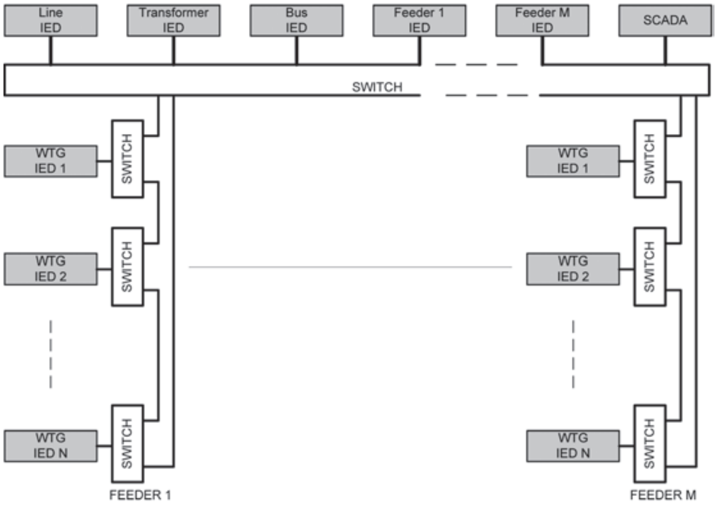

Figure 12.
Windfarm Communications Network Topology

Each wind turbine has a multifunction protection IED that would provide electrical fault protection for the generator and tower cable, as noted above. In addition to providing "local" protection for wind turbine equipment, the WTG IED features IEC61850 protocol support so as to provide the transfer trip capabilities.

The physical arrangement of the components of the windfarm dictates a network arranged in a ring-architecture for each feeder. In an Ethernet network, it is not permissible to have more than one path to a particular device. Therefore ring topologies could not be configured with early generation switches. However the latest generation of Ethernet switches provides support for Rapid Spanning Tree Protocol (RSTP). RSTP enabled switches exchange information to ensure that only one switch provides a path to a device. If a failure occurs in the enabled path, the switches will automatically reconfigure the network to re-establish a path to the device in as little as 5 milliseconds. The ring topology allows for the failure of any one path with no loss of communications to any device. A single switch failure results in the loss of communications to only one device. However, its peers on the network will quickly detect the loss of this device. This would allow the IEDs to automatically adapt to the communications failure. For instance The WTG IED could enable voltage tripping only in the case that communications with the feeder IED is lost.

8. Transfer Tripping Performance

Table 1 illustrates timing sequence for a feeder fault using the transfer trip solution. The timing analysis above assumes a breaker clearing time of 60 ms. The time required to process and transmit the GOOSE message across the network is 8 ms. Tripping of the feeder breaker by the IED is delayed by 30 ms to ensure that all of the WTGs are disconnected prior to clearing the fault. The Ethernet switches present a negligible time delay and is not included in Table 1.

Event #	Description	Time (ms)
1	Feeder Ground Fault	0
2	Feeder IED detects fault and send transfer trip	32
3a	WTG IEDs receive transfer trip & operate	8
4a	WTG breakers open	60
	WTG clearing time	**100**
3b	Feeder IED time delay	30
4b	Feeder breaker opens	60
	Feeder clearing time	**122**

Table 1.
Transfer Trip Timing

Another application would be for the WTG IED to issue a "block" command upon detection of a fault condition within the wind turbine transformer or tower cable. If such a fault occurs, the potential to cause nuisance tripping on the feeder can occur. IED2, as seen in Figure 1, provides protection for the wind tower transformer and cable, and can simultaneously trip the MV breaker as well as send a block command to the feeder IED located in the substation. This block command allows for the feeder to stay on-line and avoids disconnecting the remainder of the WTGs.

In addition to transfer trip and blocking commands, the network architecture also enables the windfarm operator to take advantage of the detailed diagnostics and metering capabilities inherent in the WTG IEDs. The current generation of microprocessor based protective IEDs contain detailed event logs, current/voltage waveform recorders, metering and other diagnostic information that prove valuable in the diagnosis of fault and system disturbances.

9. Summary

It has been demonstrated in this paper that there are aspects of a windfarm configuration that require consideration when designing the protective system. One important aspect is the need to disconnect the WTGs before isolating the feeder during a ground fault. A novel method has been presented that achieves this, alleviating the need for a grounding source on each feeder. This reduction in equipment translates into increased system reliability as well as significant cost savings for the windfarm operator. This solution makes extensive use of GOOSE messaging and leverages pre-existing system components, specifically fiber Ethernet between wind turbines, industrialized Ethernet switches and IEC61850 compliant IEDs. GOOSE messaging can also be extended to various other protection, automation, and operational applications.

10. References

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