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OPERATING LOGIC OF THERMAL ENERGY STORAGE SYSTEMS

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ABSTRACT

Thermal energy storage systems are integrated with concentrated solar thermal power plants to extend their operation beyond sunshine hours. They can also be used to boost their output during cloudy conditions. There are many types of thermal energy storage systems, but this article seeks to develop a broad operating logic that is applicable to most schemes. The article will describe how heat is moved into and out of thermal energy storage systems during operation, namely their charging and discharging processes.

INTRODUCTION

Concentrated solar power (CSP) plants produce electricity using generators attached to turbines supplied with steam that is generated using heat acquired by focusing sunbeams onto a heat transfer fluid (HTF). The HTF gives up its heat to a conventional Rankine cycle power plant. Integrating a TES system into a CSP plant will, as shown in Figure 1, will guarantee a continuous and smooth supply of electricity. The TES system can be thermally charged during the day then it can be thermally discharged at night or during cloudy conditions.

Keywords: Solar energy, thermal energy storage.

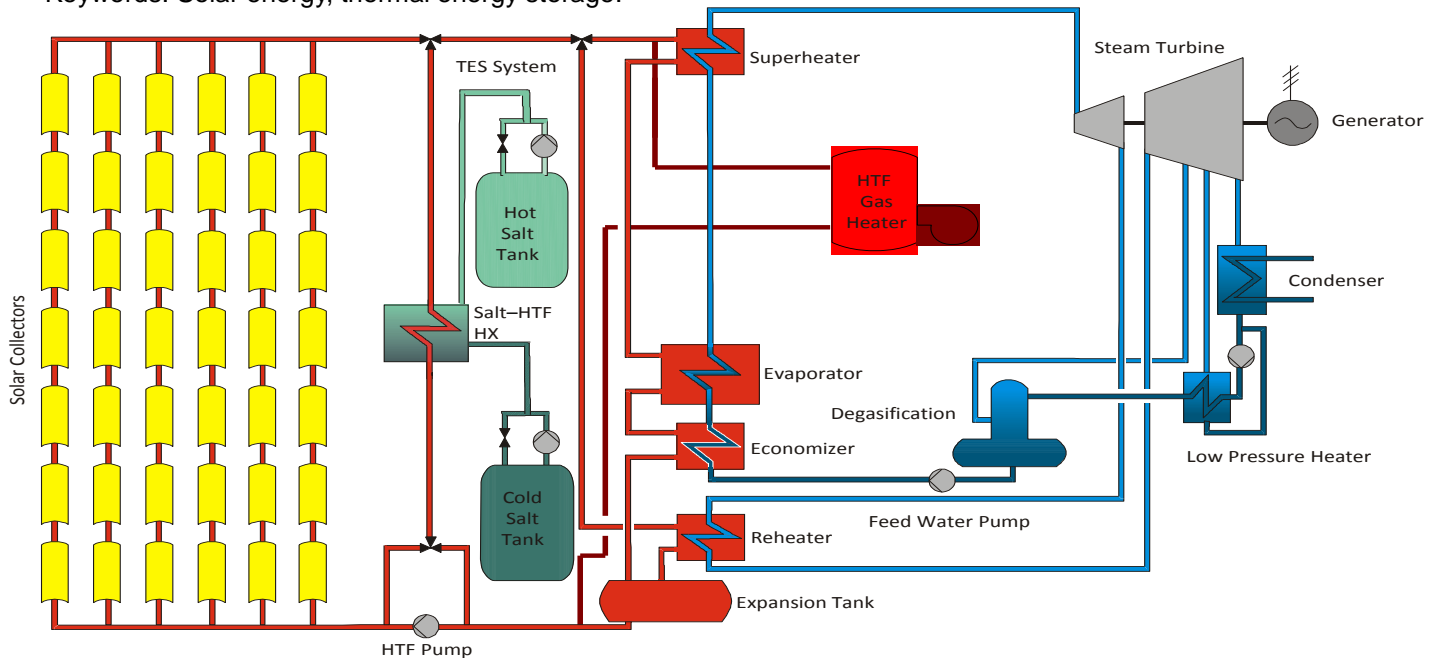


Figure 1. Dual-tank molten salt scheme in a CSP plant

The most common TES system is a dual-tank molten salt scheme. It consists of two equally-sized well-insulated tanks holding molten salt at two different temperatures. Each tank has a pump connected to its outlet pipe plus an inlet pipe. Furthermore, a heat exchanger is placed between the two tanks designed to transfer heat from the solar field (SF) to the TES system as well as from the TES system to the power block (PB) via a HTF.

Adding heat to the TES system is termed *charging*, while withdrawing heat from the TES system is termed *discharging*. During the TES charging process, molten salt is pumped from the cold tank to the hot tank through a heat exchanger where hot HTF coming from the SF gives up heat to the molten salt. Whereas, during the TES discharging process, molten salt is pumped from the hot tank to the cold tank through a heat exchanger where the molten salt gives up heat to cold HTF bound for the PB.

Salt holding tanks are very well insulated; however, a small amount of heat loss takes place. Subsequently, a fossil fuel auxiliary heater (AUX) is usually attached to the TES system to avoid freezing during extended periods lacking solar resource input. Those auxiliary heaters are usually fueled by natural gas. Salt freezing is a serious operational menace that must be avoided by all means.

Heat can also be stored in water, reinforced concrete, rocks, and other mediums of high heat capacity. Molten salt thermocline tanks represent another common form of TES. It consists of one large thermally-stratified tank where lower-density hot molten salt floats on top of the higher-density cold molten salt.

During the TES charging process, colder molten salt is pumped from the bottom of the tank to the top of the tank through a heat exchanger where hot HTF coming from the SF gives up heat to the molten salt. Whereas, during the TES discharging process, hotter molten salt is pumped from the top of the tank to the bottom of the tank through a heat exchanger where the molten salt gives up heat to cold HTF bound for the PB.

LOGIC

A CSP plant can be thought of as a large heat processing system consisting of four modules: SF, AUX, TES, and PB exchanging heat by way of a HTF network that moves heat across H₂O-HTF and Salt-HTF heat exchangers as well as HTF-AUX heaters. Figure 2 maps out heat flow in a conventional CSP plant.

The SF outputs heat to the PB for power generation and to the TES for storage. The AUX outputs heat to the PB to boost its power generation, to the TES to prevent salt freezing or to stock heat, or to the SF to prevent HTF freezing if necessary. Last but not least, the TES outputs heat to the PB for power generation.

Depicting TES operation is the aim of this article; therefore, only TES charging and discharging heat flow operations were addressed. Block diagrams will be developed to denote the logic of how heat is transferred from the SF to the TES ($q_{SF \rightarrow TES}$), from the AUX to the TES ($q_{AUX \rightarrow TES}$), and from the TES to the PB ($q_{TES \rightarrow PB}$). Those block diagrams can then be used to configure the distributed control system (DCS) of the TES-integrated CSP plant to optimize plant operation.

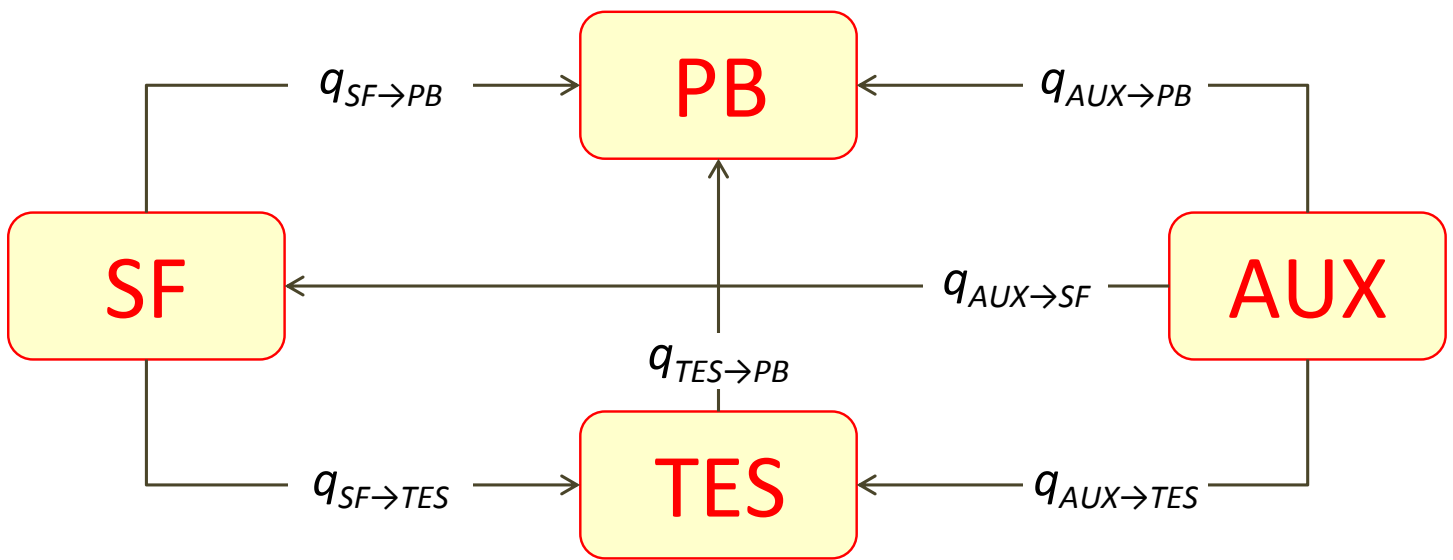


Figure 2. Heat flow in a standard CSP plant

1. Normal Charging Process ($q_{SF \rightarrow TES}$)

The heat transfer rate from the SF to the TES system represents the normal TES charging process. Heat collected by the SF is divided between the PB and the TES. The PB receives a predetermined amount of that heat, while the TES receives the remainder. Detailed calculations for the total amount of heat collected in the SF have been published before [1].

The PB would normally receive the maximum amount of heat that it can process for electric generation; however, that may not be always the case. PB heat load can drop due to reduced electricity demand or maintenance.

No heat will be forwarded from the SF to the TES if it would cause the TES to exceed its maximum allowable thermal energy. If the current heat content of the TES plus the integrated amount of the TES minimum charging rate minus its heat loss would exceed its maximum allowable thermal energy, the TES cannot be charged. Else, the TES charging rate equals the rate of heat collected by the SF minus the rate of heat forwarded to the PB, subject to TES charging limits of course.

A block diagram denoting the logic of the TES normal charging process by the SF is illustrated in Figure 3. No TES charging takes place if it would put it above its maximum allowable thermal energy limit or if the charging rate is smaller than the TES lower charging limit.

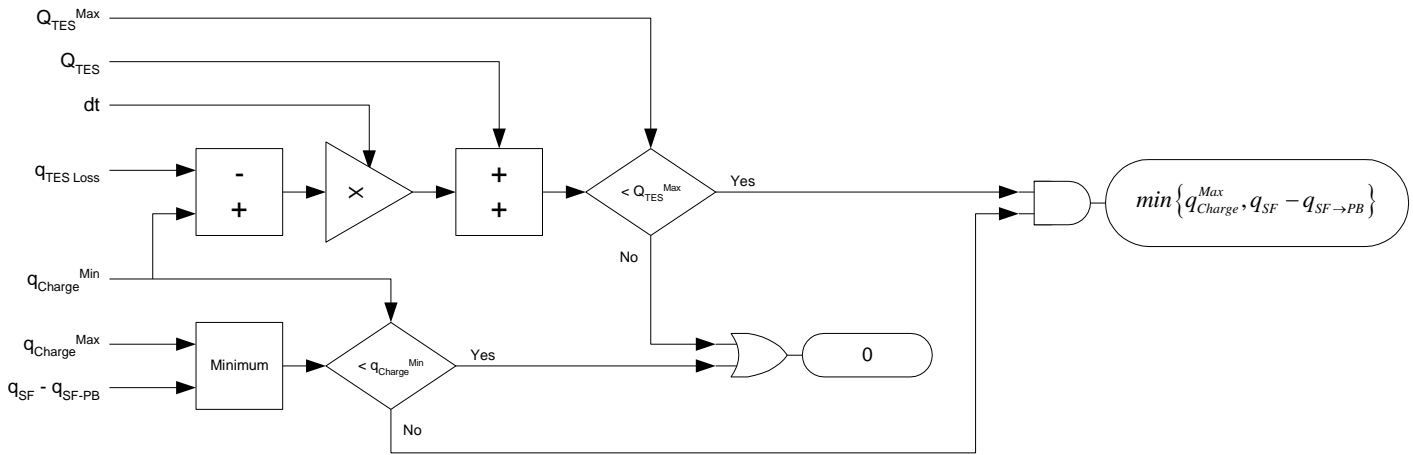


Figure 3. $q_{SF \rightarrow TES}$: normal charging process

2. Freeze Protection Process ($q_{AUX \rightarrow TES}$)

The heat transfer rate from the AUX system to the TES system to inhibit salt freezing is another TES charging process that must be considered. It is a nonstandard process that comes about to prevent salt freezing during extended periods of little or no solar resource.

Under the freeze protection nonstandard TES charging process, no heat will be forwarded from the AUX to the TES if the TES is not vulnerable to dropping below its minimum allowable thermal energy. If the heat content of the TES plus the integrated amount of heat transfer rate from the SF to the TES minus its heat loss exceeds its

minimum allowable thermal energy, the TES will not be auxiliary charged. If the TES is vulnerable to dropping below its minimum allowable thermal energy, that is if the heat content of the TES plus the integrated amount of heat transfer rate from the SF to the TES minus its heat loss drops below its minimum allowable thermal energy, the TES will need to be charged by the AUX. The TES charging rate equals the residual TES thermal energy incremented over time plus its heat loss minus the rate of heat forwarded from the SF to the TES, subject to TES charging limits.

A block diagram denoting the logic of the freeze protection nonstandard TES charging process by the AUX is illustrated in Figure 4.

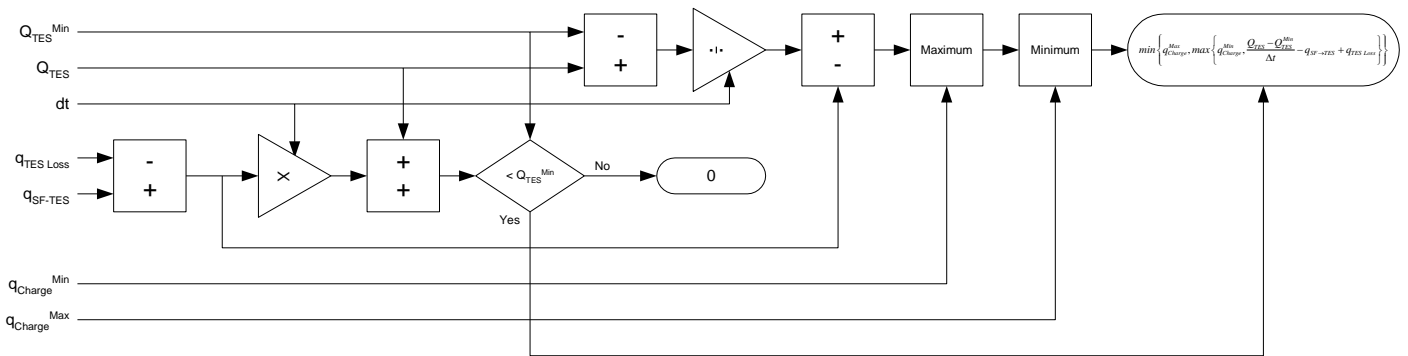


Figure 4. $q_{AUX \rightarrow TES}$: freeze protection process

3. Energy Storage Augmentation Process ($q_{AUX \rightarrow TES}$)

The heat transfer rate from the AUX to the TES system for freeze protection purposes was covered above; still, there is another nonstandard TES charging process that must be considered. It can occur at times when it makes economic sense to store energy and release it later. This can emerge periodically when auxiliary heating costs drop or when the price of electricity will surge at a later time as dictated by a power purchase agreement (PPA).

Under this energy storage augmentation nonstandard TES charging process, no heat will be forwarded from the AUX to the TES if the TES is vulnerable to exceeding its maximum allowable thermal energy. If the heat content of

the TES plus the integrated amount of heat transfer rate from the SF to the TES minus its heat loss exceeds its maximum allowable thermal energy, the TES will not be auxiliary charged. Else, the TES auxiliary charging rate equals the potential TES thermal energy incremented over time plus its heat loss minus the rate of heat forwarded from the SF to the TES, subject to TES charging limits. The potential TES thermal energy is the difference between its maximum allowable thermal energy and its current thermal energy content.

A block diagram denoting the logic of the energy storage augmentation nonstandard TES charging process by the AUX is illustrated in Figure 5.

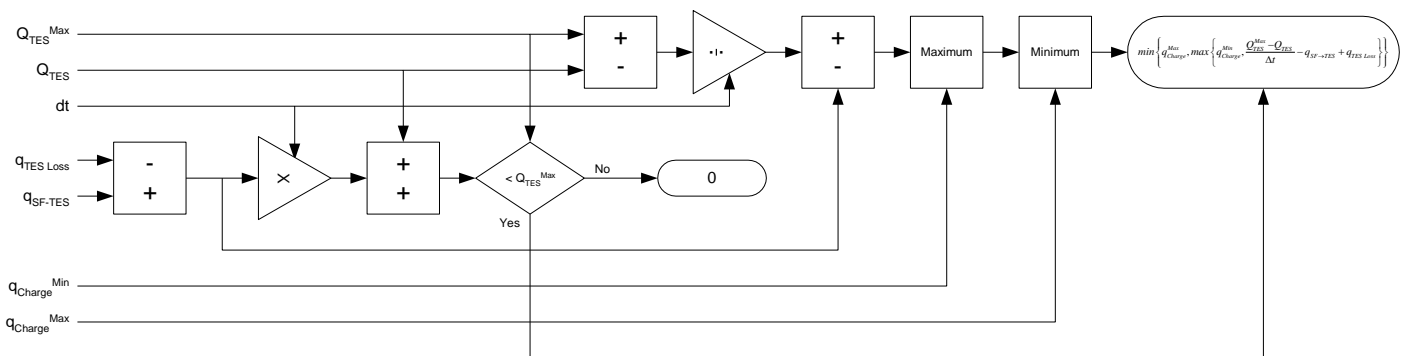


Figure 5. $q_{AUX \rightarrow TES}$: energy storage augmentation process

4. TES Discharging Modes ($q_{TES \rightarrow PB}$)

The heat transfer rate from the TES system to the PB denotes the TES discharging process. Heat stored within the TES system is discharged to the PB to augment or extend its operation into periods of little or no solar resource such as nighttime and cloud covers in addition to the course of SF maintenance.

There are three distinct cases that describe how heat is transferred from the TES to the PB, which will be dealt with independently. No heat will be discharged from the TES system to the PB if it would cause the TES to drop below its minimum allowable thermal energy. If the current heat content of the TES plus the integrated SF and AUX charging rates minus TES minimum discharging and its heat loss rates are less than the minimum allowable TES heat level, the TES cannot be discharged. Evidently, the TES should not be discharging heat if it is being charged by either the SF or AUX. This situation is

designated below as Case 1. Else, the TES discharging rate can be set depending on the availability of the SF.

Alternatively, if the current heat content of the TES plus the integrated SF and AUX charging rates minus TES minimum discharging and its heat loss rates surpass the minimum allowable TES heat, the TES can discharge heat to the PB. TES discharging is carried out either to augment PB heat input during times of declined SF output, designated as Case 2, or to extend PB heat input during times of no SF output, designated as Case 3.

A block diagram denoting the logic that defines a TES discharging mode is illustrated in Figure 6. The variable: $t_{Off \rightarrow On}$ is the time remaining for the SF to become available. So, it equals zero while the SF is deployed, or in operation, and it is above zero while the SF is stowed, or during nighttime and cloud cover periods. Case 1 represents times when no TES discharging is possible, $q_{TES \rightarrow PB} = 0$. The logics of Case 2 and Case 3 are detailed below to arrive at a suitable $q_{TES \rightarrow PB}$ calculation scheme.

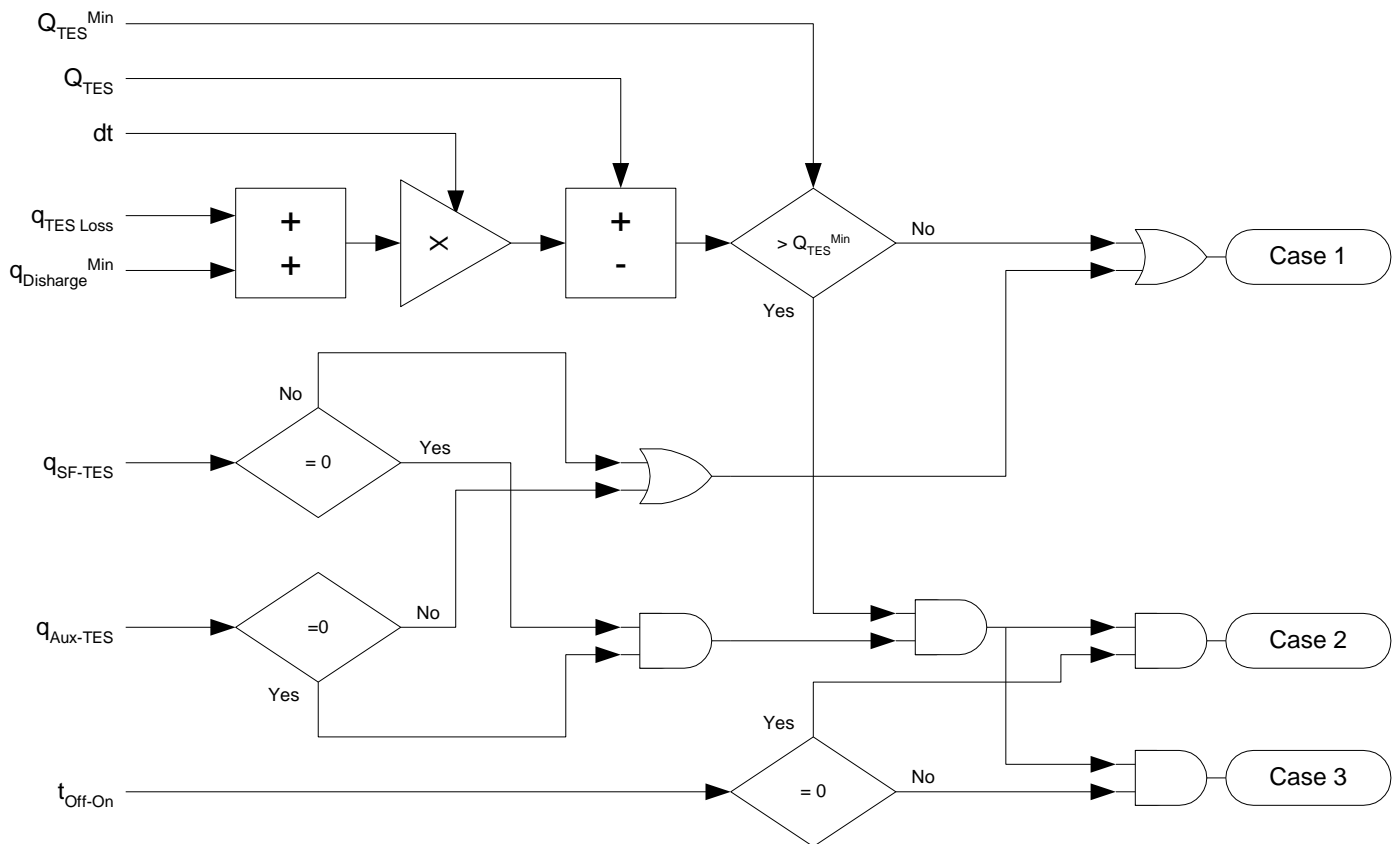


Figure 6. $q_{TES \rightarrow PB}$: TES discharging modes

5. Power Generation Augmentation Process ($q_{TES \rightarrow PB}$)

If the current heat content of the TES minus the TES minimum discharging and its heat loss rates surpass the minimum allowable TES heat, the TES can discharge heat to the PB. The power generation augmentation process is a nonstandard TES discharging process carried out to boost PB heat input during times of declined SF output. It is designated as Case 2 above.

During this nonstandard TES discharging process, the TES discharging rate is set equal to the minimum of the following two quantities: the residual TES thermal energy incremented over time minus its heat loss, and the

maximum PB heat load minus the rate of heat forwarded from the SF to the PB subject to TES discharging limits.

The logic of Case 2 seeks to maximize electric generation by maximizing PB heat load; however, that may not be the desired outcome at times. Optimal PB heat load can be reduced due to low demand or maintenance or low electricity selling prices dictated by the PPA. Therefore, the logic of Case 2 may need to be revisited to optimize the TES discharging rate.

A block diagram denoting the logic of the power generation augmentation nonstandard TES discharging process is illustrated in Figure 7.

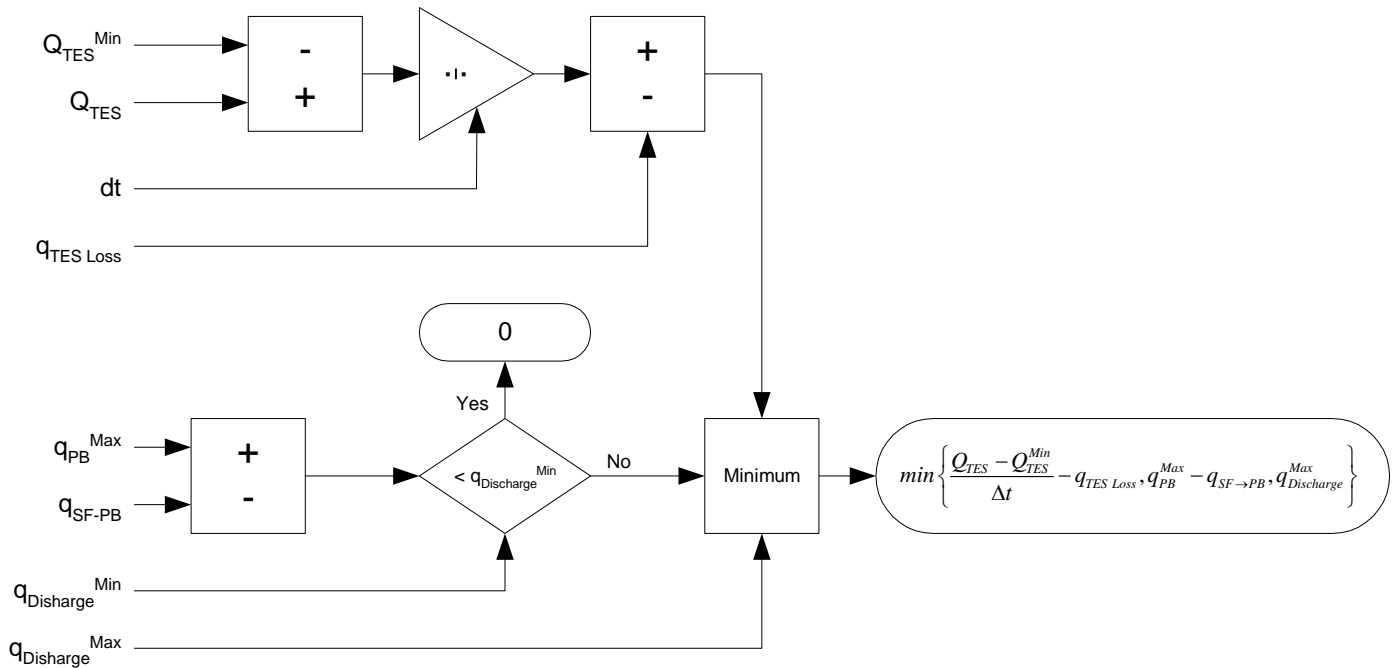


Figure 7. $q_{TES \rightarrow PB}$: power generation augmentation process

6. Normal Discharging Process ($q_{TES \rightarrow PB}$)

If the current heat content of the TES minus the TES minimum discharging and its heat loss rates surpass the minimum allowable TES heat, the TES can discharge heat to the PB. The normal TES discharging process is carried out to extend PB heat input during times of no SF output. It is designated as Case 3 above.

During this standard TES discharging process, the TES discharging rate is set equal to the residual TES thermal energy evenly dispensed over the time left for the SF to come on-line, subject to TES discharging limits. The time left for the SF to come on-line can be considered equal to the time remaining for sunrise. The time left for the SF to come on-line can be extended if clouds are expected to delay the onset of the solar resource or if the SF is under maintenance, therefore delaying its deployment.

A special case arises at low TES thermal energy levels. The TES discharging rate is set equal to the minimum TES discharging limit if the residual TES thermal energy is too small to be dispensed evenly over the time left for the SF to come on-line. This is upheld until the integrated residual TES thermal energy becomes lower than the TES lower discharging limit, at which no further heat can be extracted from the TES.

The logic of Case 3 seeks to optimize electric generation by evenly releasing the TES thermal energy to the PB

over the time left for the SF to come on-line; however, that equal dispensing may not be the preferred TES discharging scheme. Optimal PB heat load can vary with time due to varying demand or maintenance or fluctuating electricity selling prices dictated by the PPA. Therefore, the logic of Case 3 may need to be revisited to optimize the TES discharging rate.

A block diagram denoting the logic of the normal TES discharging process is illustrated in Figure 8.

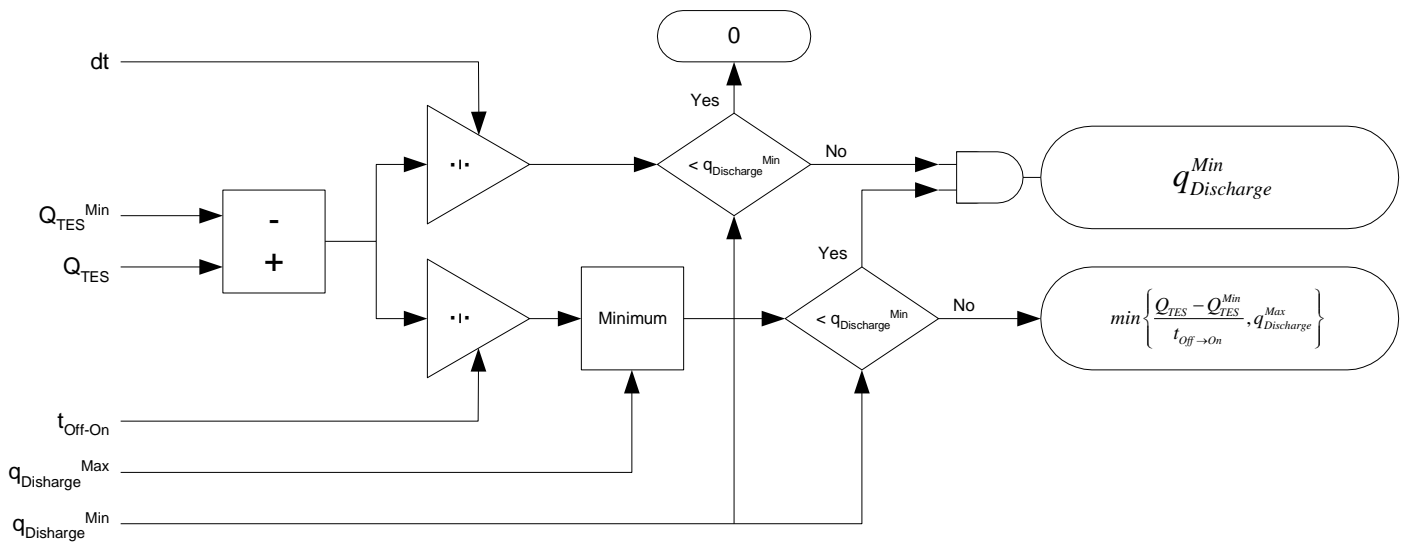


Figure 8. $q_{TES \rightarrow PB}$: normal discharging process

CONCLUSION

TES systems are used to augment or extend power generation in CSP plants into periods of little or no solar resource. Adding heat to the TES system is known as charging, while withdrawing heat from the TES system is known as discharging. A TES system is thermally charged during sunlight hours with excess heat generated in an over-sized SF supplying heat to a PB. A TES system is thermally discharged during nighttime or cloudy periods releasing heat to a PB to boost or extend power output.

The most common TES system is a dual-tank molten salt scheme. It consists of two equally-sized well-insulated tanks holding molten salt at two different temperatures. The temperature of the cold tank is set marginally above salt freezing point, while the temperature of the hot tank is slightly below the HTF SF return temperature.

Block diagrams detailing how heat is moved into and out of a TES system, also called charging and discharging operations, were developed. The block diagrams denote an operating logic applicable to most TES schemes and can be used to configure the DCS of the TES-integrated CSP plant to optimize plant operation.

Heat collected by the SF is shared between the PB and the TES. The PB normally receives the maximum amount of heat that it can process for electric generation, while the remaining heat is stored in the TES system. No heat will be forwarded to the TES from the SF if it would cause it to exceed its maximum allowable thermal energy. In addition, no heat will be forwarded from the AUX to the TES if the TES is either not vulnerable to dropping below its minimum allowable thermal energy or is vulnerable to exceeding its maximum allowable thermal energy. In contrast, no heat will be discharged from the TES system to the PB if it would cause the TES to drop below its minimum allowable thermal energy.

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NOMENCLATURE

AUX	auxiliary heater
CSP	concentrating solar power
HTF	heat transfer fluid
PB	power block
PPA	power purchase agreement
q	heat flow, MW
Q	heat, MWh
SF	solar field
t	time, hour
TES	thermal energy storage

CITATION

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